D^0-$\bar{D}^0$ mixing with the full CDF dataset

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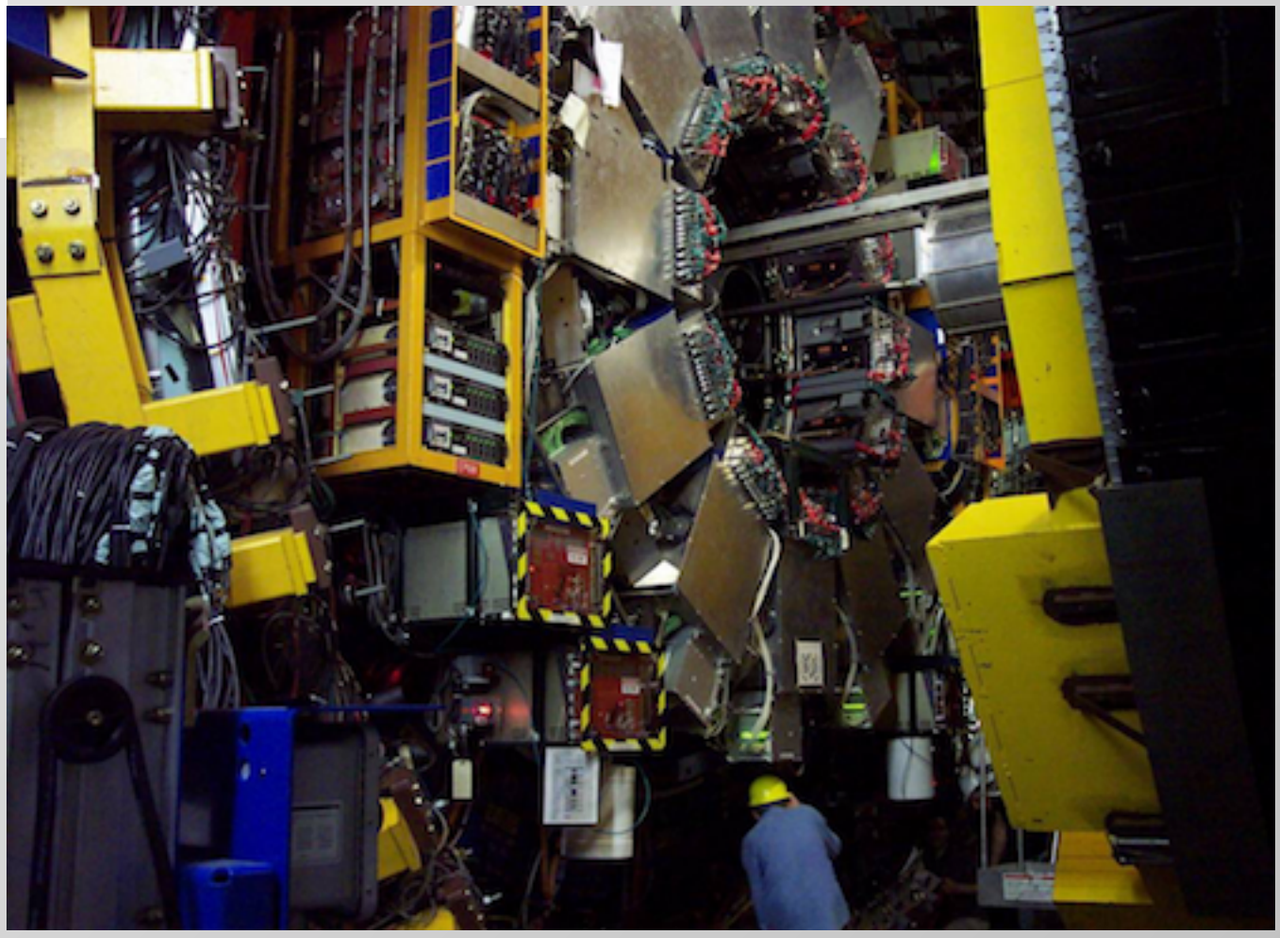
on behalf of the CDF Collaboration

Joint Experimental-Theoretical Physics Seminar

April 12, 2013



Charm Mixing Overview

(More extensive overview available on the PDG web page)

Neutral Meson Mixing

- Particle - antiparticle oscillation
- Production eigenstates ≠ mass eigenstates

$$\left|D^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D_1\right\rangle + \left|D_2\right\rangle\right) \qquad \left|\overline{D}^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|D_1\right\rangle - \left|D_2\right\rangle\right)$$

Assuming no CP violation

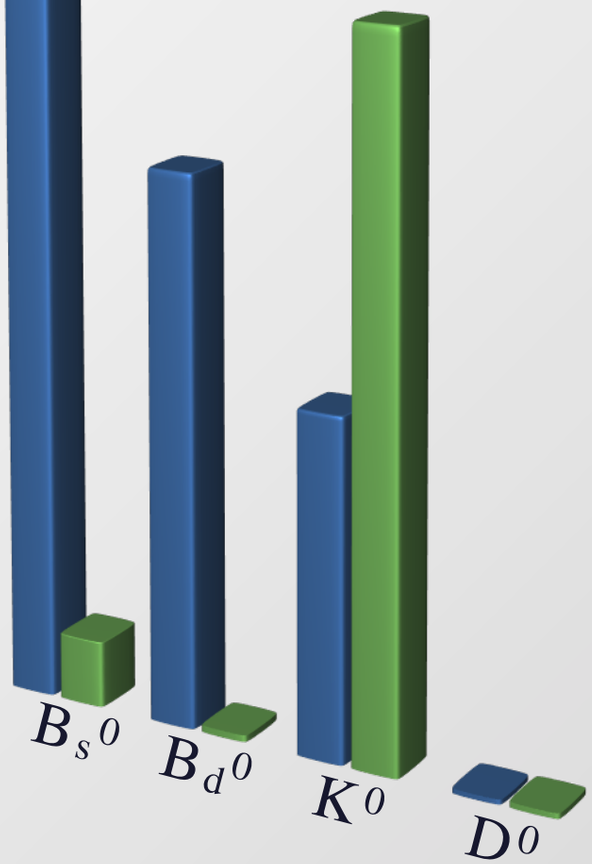
- Time evolution of mass eigenstates

$$i\frac{\partial}{\partial t}\left|D_{1,2}(t)\right\rangle = \left(M - \frac{i}{2}\Gamma\right)\left|D_{1,2}(t)\right\rangle$$

$$\left|D_{1,2}(t)\right\rangle = \left|D_{1,2}(0)\right\rangle e^{-t\left(\frac{1}{2}\Gamma_{1,2} + iM_{1,2}\right)}$$

Meson Mixing

Mixing	x	y
B_s^0	26.6	0.092
B^0	0.77	0.009
K^0	0.474	0.997
D^0	0.0065	0.0073



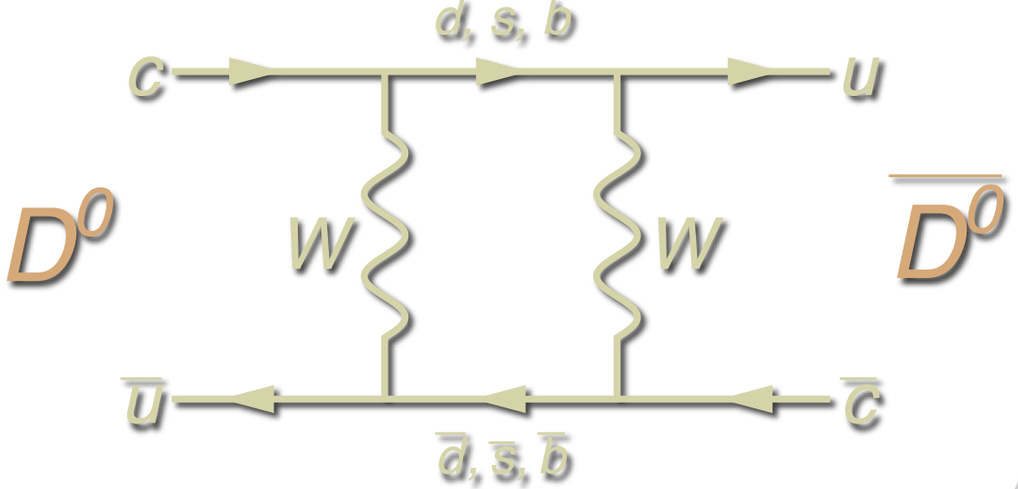
$$x \equiv \frac{M_2 - M_1}{\Gamma}$$

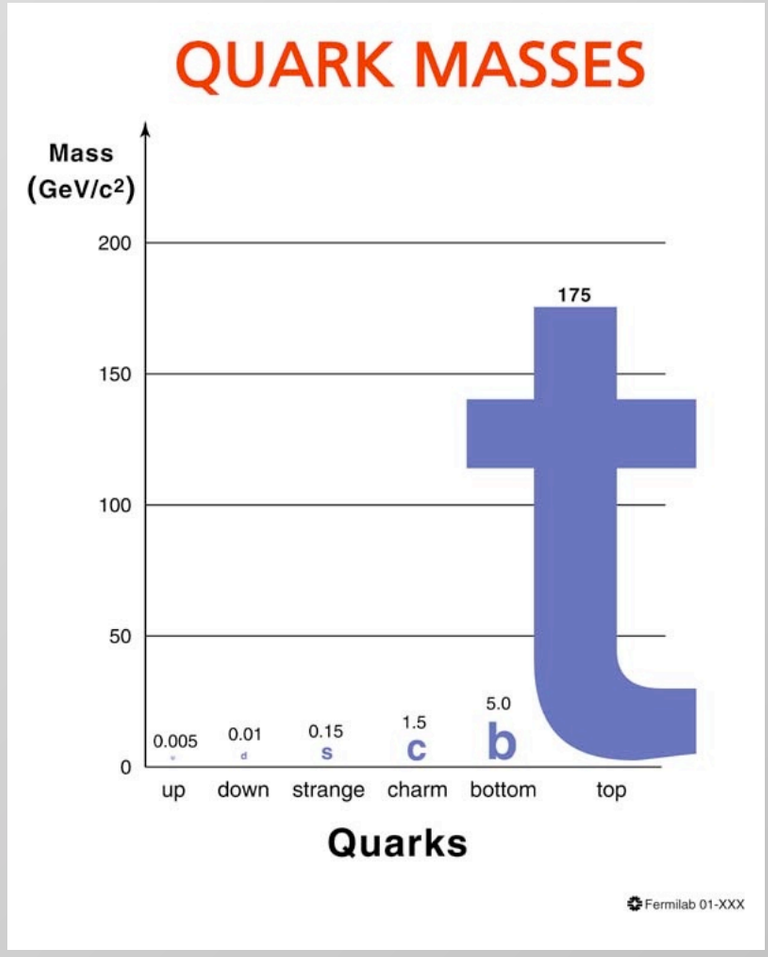
$$y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

- Charm mixing is small
- Despite D mesons being seen before B mesons, charm mixing was only observed recently
  - kaon mixing seen 1962
  - beauty mixing seen 1987
  - B_s oscillations observed 2006
  - first evidence of charm mixing was in 2007
  - first single measurement observation of charm published March 2013 (LHCb)

Calculating Mixing

- Kaon and Beauty mixing due to contributions from the box diagrams
  - superheavy quarks (i.e. top) destroying GIM cancellations
- For charm, those contributions are small
  - $O(10^{-5})$ or less
  - down-type quarks (no top)

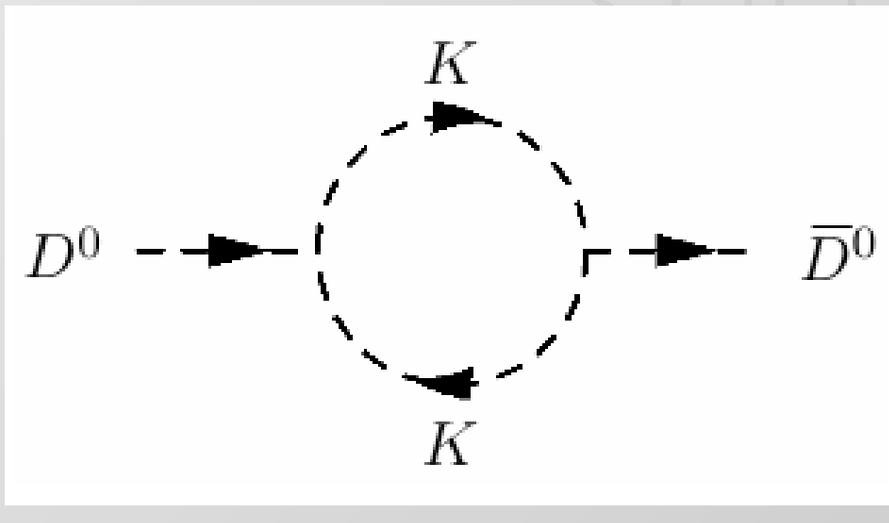




Calculating Mixing

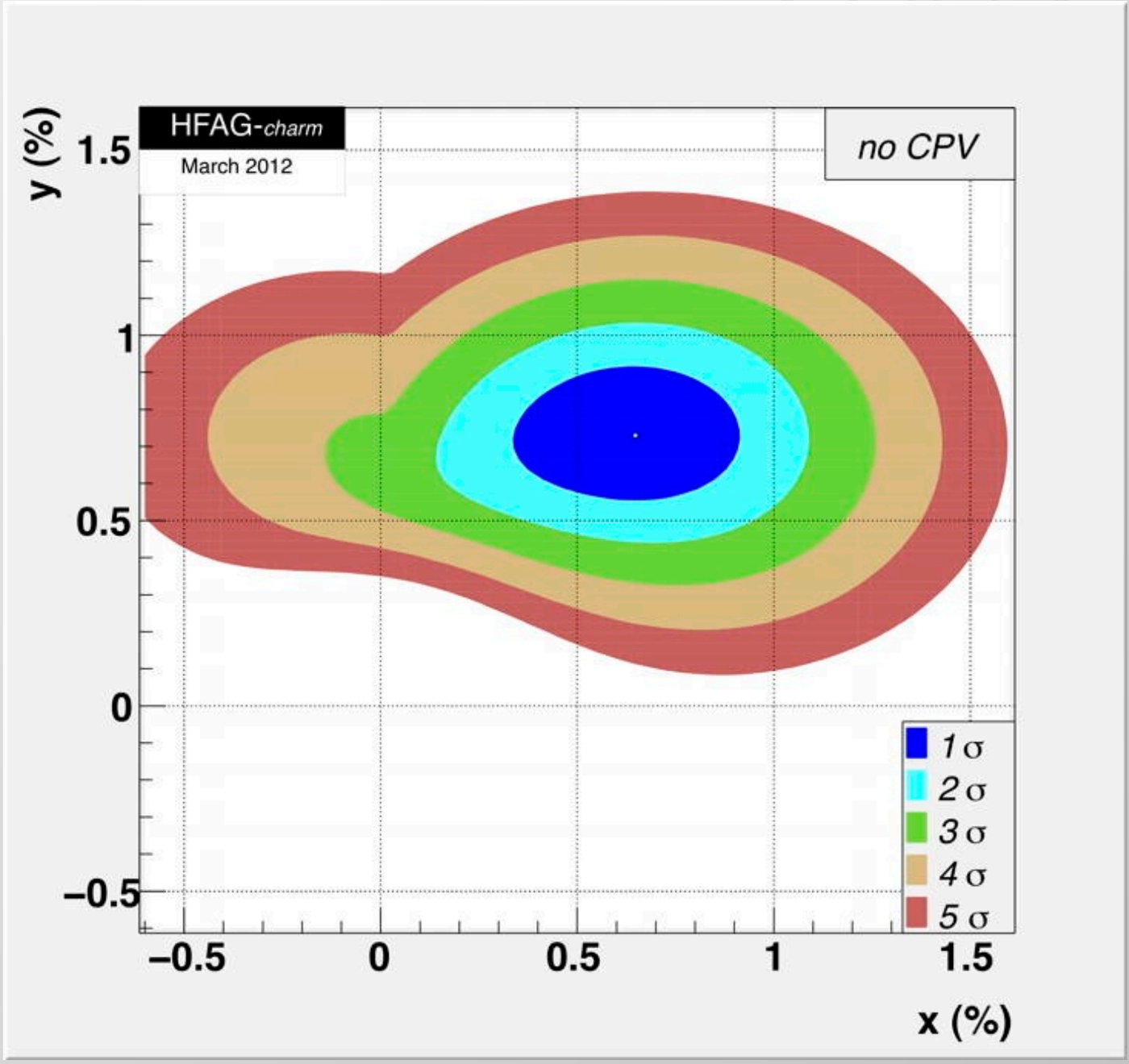
- Long-distance contributions are important for charm mixing
  - $O(10^{-2})$ or less
  - D^0 and $\overline{D}^0$ can decay to common hadronic states like KK or $\pi\pi$
- harder to get theory predictions
  - non-perturbative, model dependent
  - only mixing involving up-type quarks
  - CP violation studies (New Physics)
  - as results get more precise, can reduce the number of viable theory models
    - also relate mixing to rare decays

      (like $D^0 \to \mu\mu$)



Charm Mix Measurements

- Heavy Flavor Averaging Group has combined all D^0 decay modes and experimental results
  - semi-leptonic decays, $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$,lifetime differences (KK, $\pi\pi$), $K^0\pi^-\pi^+$, $K^0K^-K^+$
- The no-mixing hypothesis excluded at 10.2σ significance
  - Only a few measurements have exceeded 3σ



Charm Mixing with $D^* \rightarrow \pi_s D^0, D^0 \rightarrow K\pi$

D^*, D^0, $K\pi$

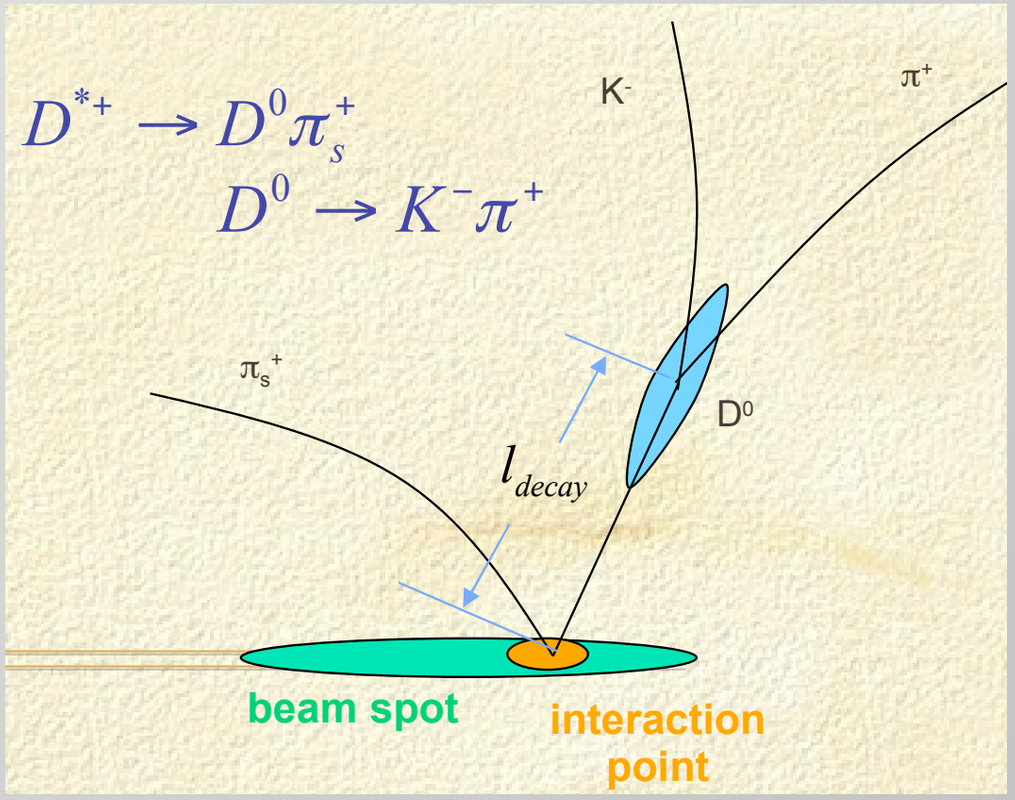
- For this analysis, need:
  - Proper decay time for time evolution
  - Identify charm flavor at production
  - Identify flavor at decay
- $D^* \rightarrow \pi_s D^0$, $D^0 \rightarrow K\pi$
  - Measure decay length from the beamline

"s" stands for softer momentum

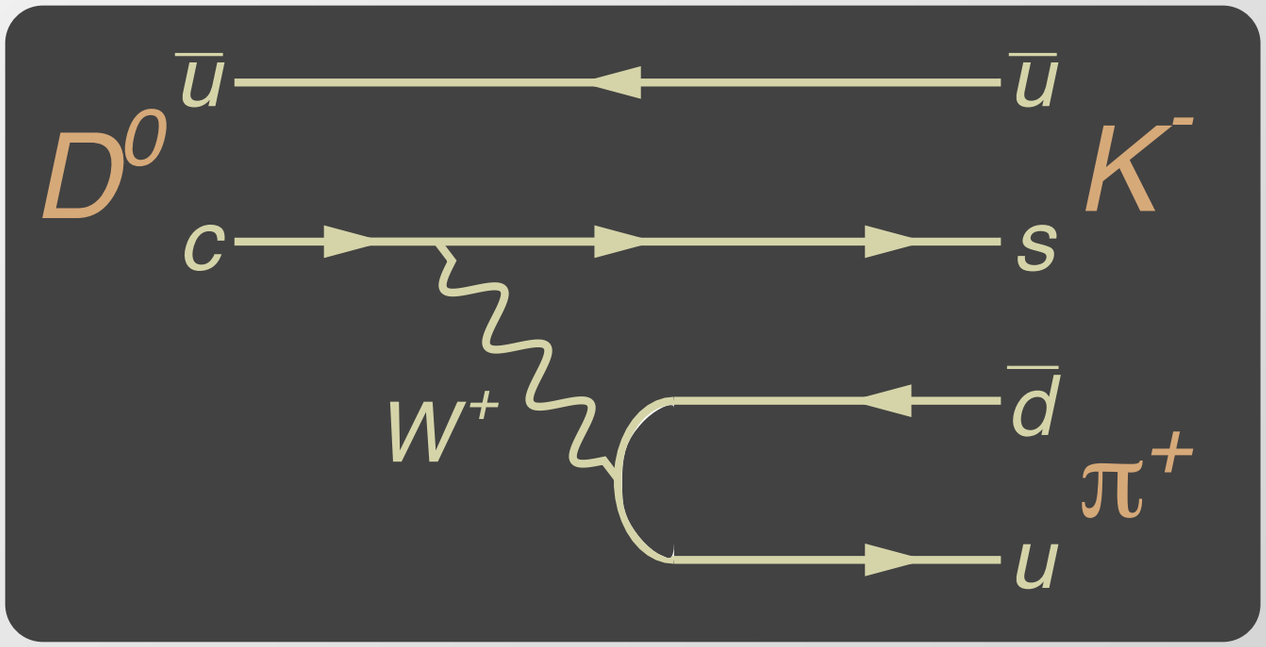
Requiring a D* also improves signal:background

- $\pi_s^+ \longmapsto D^0$

  $\pi_s^- \longmapsto \bar{D}^0$
- $K^+\pi^-$ or $K^-\pi^+$

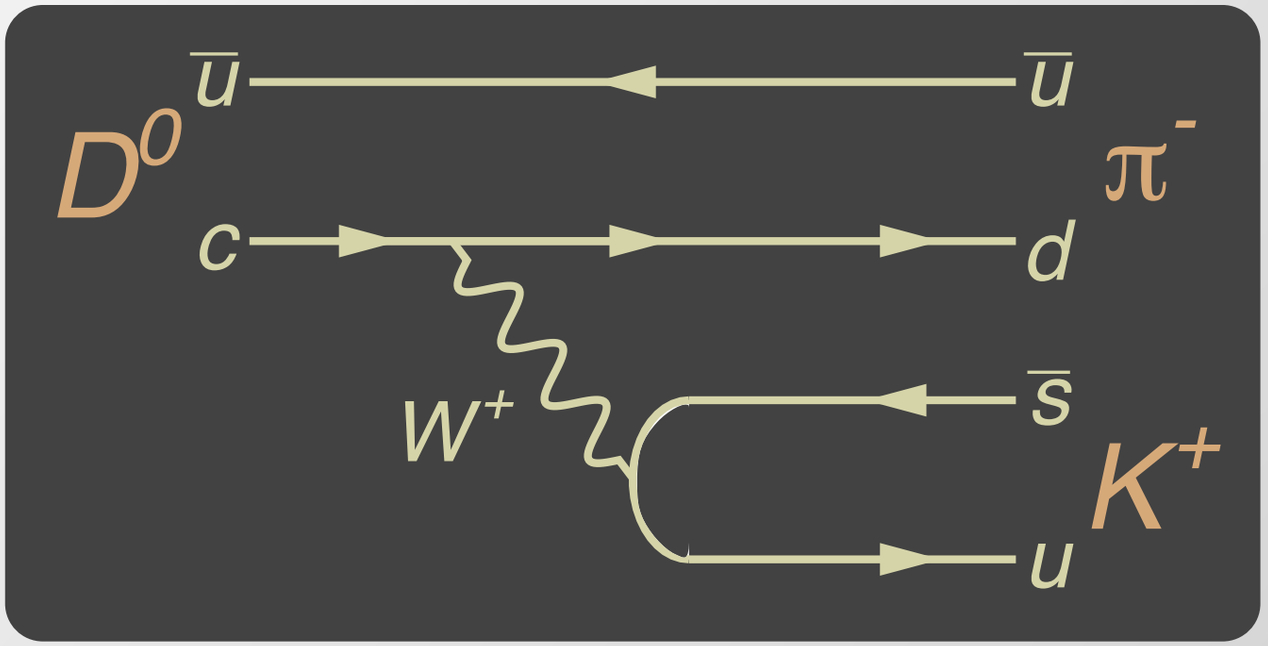


Lingo: "Right-sign"



- "Right-Sign" events have pions with the same charge
  - $D^{*+} \rightarrow \pi_s^+ \quad \pi^+ K^-$
  - Cabibbo favored (CF) D^0 decay

Lingo: "Wrong-sign"



- "Wrong-Sign" events have pions with opposite charge
  - $D^{*+} \rightarrow \pi_s^+ \pi^- K^+$
  - Doubly Cabibbo suppressed (DCS) decays
  - Mixing: $D^0 \Leftrightarrow \bar{D}^0$, followed by CF decay
- RS:WS roughly 300:1

Decay Rate Ratio

- With *x*, *y* ≪ 1 and assuming no CPV, the time-dependent ratio of WS to RS events can be approximated by

$$R(t/\tau) = R_D + (t/\tau)\sqrt{R_D}\,y' + (t/\tau)^2\,\frac{x'^2 + y'^2}{4}$$

DCS to CF ratio | Interference | Mixing

(note: R_D ~ O(0.3%))

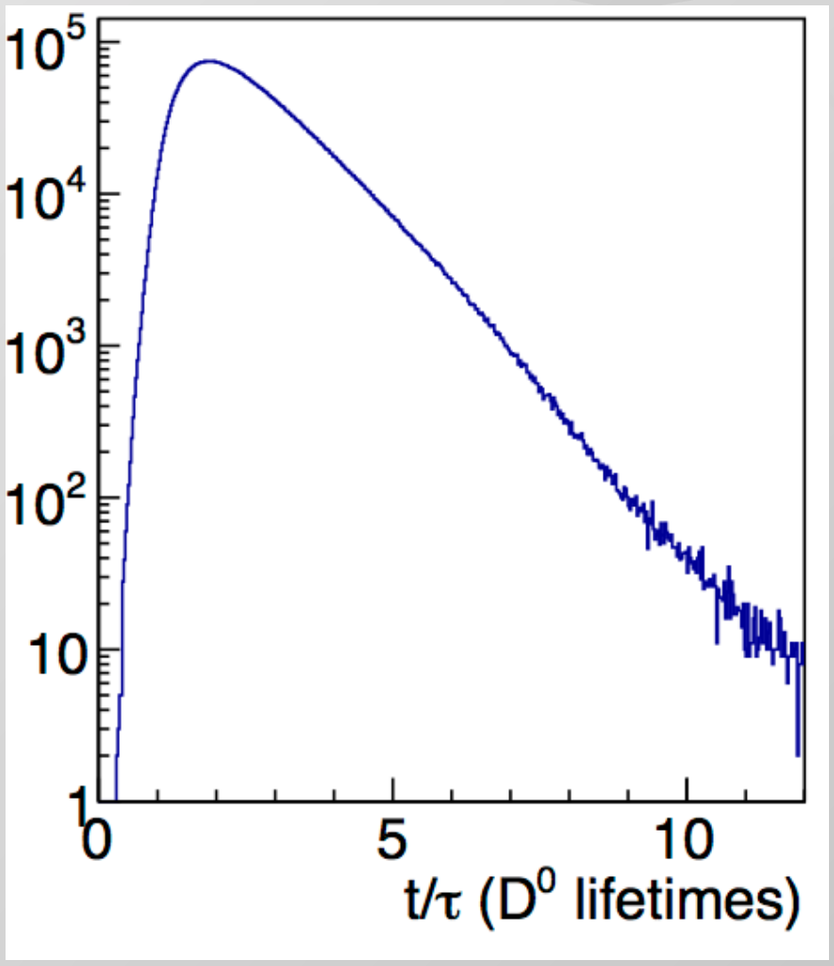
- Formula uses x′, y′ instead of x, y

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$
$$y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

  - Strong phase difference $\delta_{K\pi}$ between CF and DCS amplitudes
  - $x^2 + y^2 = x'^2 + y'$

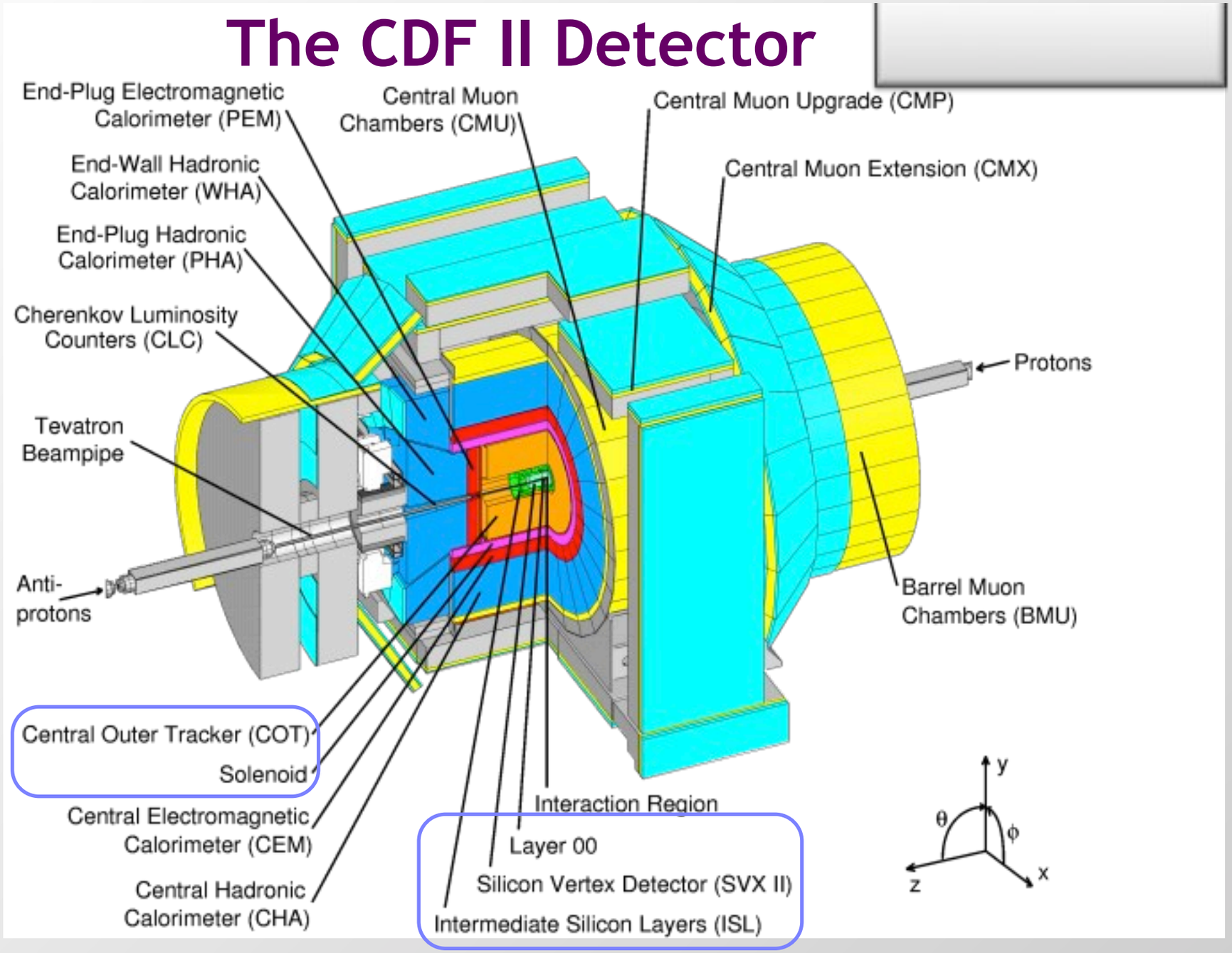
Misc Notes

- Including charge conjugate decays
  (D*+ and D*- combined)
  - simplifies systematic errors in the WS/RS ratio
- Events divided into 20 bins of decay time, ranging from 0.75-10 D^0 lifetimes
  - Bin width gets wider as the decay time increases
  - Event-weighted mean time for each bin, determined from RS D*
- Analysis precision is limited by the number of WS D*



CDF Event Selection

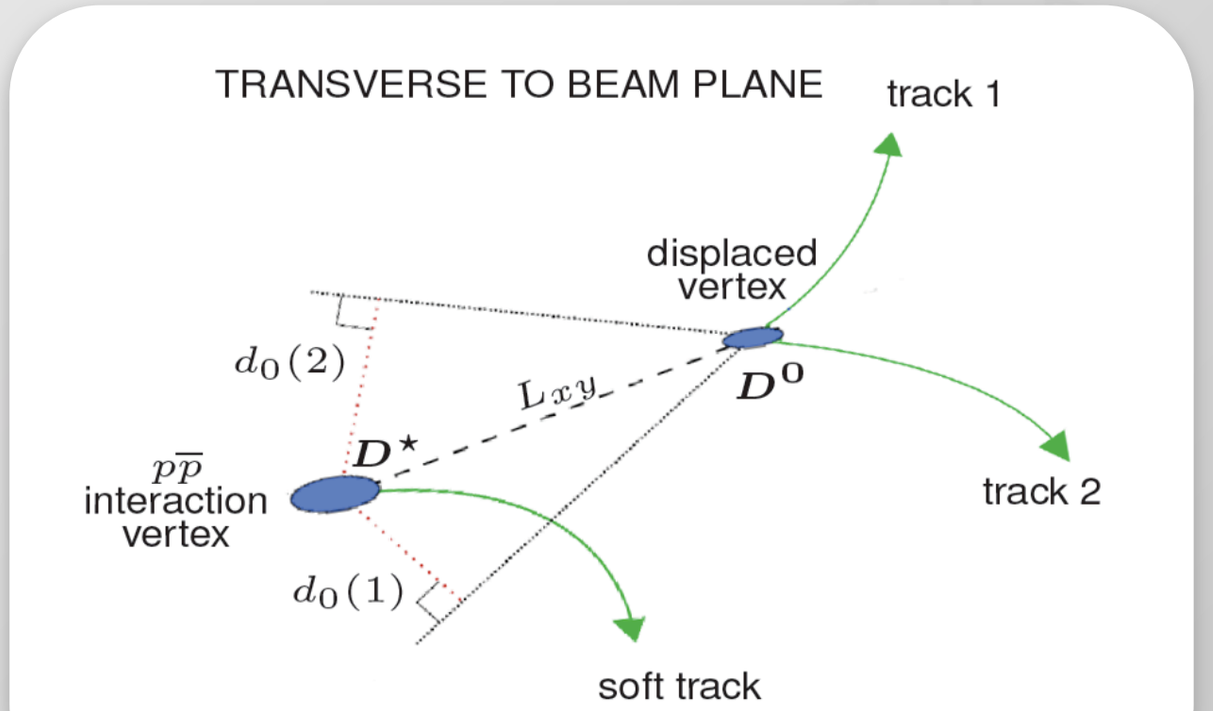
CDF II Detector



- Data collected from Feb 2002 - Sep 2011
  - $\int L \approx 9.6\ \text{fb}^{-1}$ at $\sqrt{s} = 1.96\ \text{TeV}$
- Looking at fully reconstructed D^0 decaying to charged K and π
  - silicon vertex detector surrounded by wire drift chamber (COT) in 1.4T solenoid (central tracking)
  - Particle identification using energy loss (dE/dX) in the COT

Hadronic Trigger

- CDF used a dead-timeless, high rate trigger system
- This analysis uses the hadronic trigger that requires two oppositely charged tracks in COT+SVX from a displaced vertex
  - Optimized for *B* decays, but has good charm acceptance
- The trigger tracks are used to form the $D^0 \rightarrow K\pi$ candidates
  - Additional tracks found off-line to form $D^{*+} \rightarrow \pi_s^+ D^0$ candidate

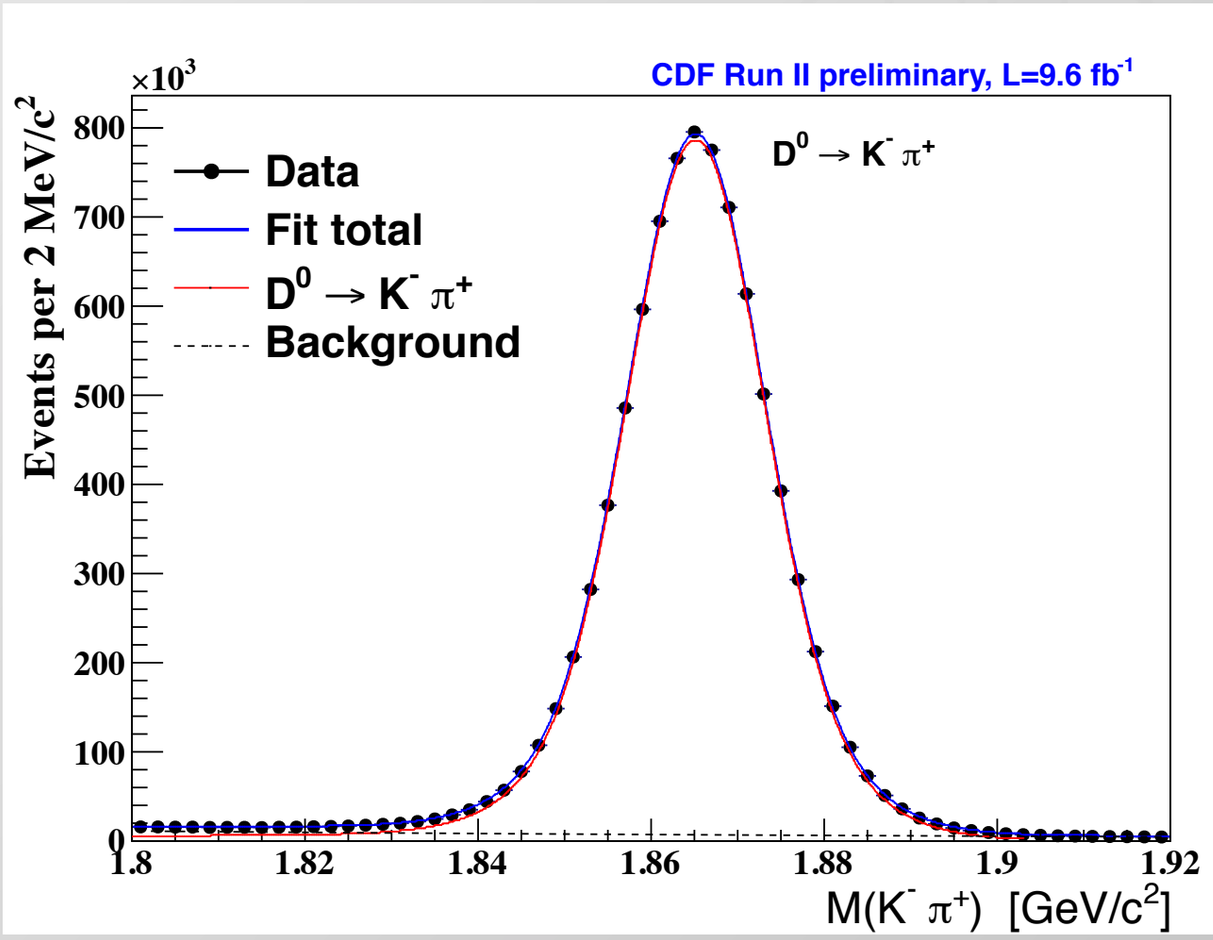


Candidate Composition

- D* produced at the beamline interaction <-- SIGNAL
- D* from secondary decays, like B mesons
  - Will have different impact parameter (d_0) from signal
- fake D* candidates: D^0 + random track
  - Different ΔM [= $M(\pi_s K\pi)$ - $M(K\pi)$ - $M(\pi_s K\pi)$] from real D*
- D^0->$K\pi$ incorrectly reconstructed as πK
  - particle identification and $K\pi$ mass distribution different from D^0
- Other D^0 backgrounds
  - D^0-> KK, D^0->$\pi\pi$, partially reconstructed charm, combinatoric background
  - smooth $K\pi$ distribution (non-peaking)

Basic Selection Cuts

- The detached vertex trigger, by itself, gives us a clean CF D^0 signal
- Basic selections:
  - $\Delta M < 30$ MeV/c^2
    - Fewer fake D* candidates
  - D^0 impact parameter d0 < 60 μm
    - Reduce D* from secondaries
  - π_s track must pass near beamline
    - Reduce obvious fake combinations
  - π_s $0.4 < pT < 2.0$ GeV/c^2
    - reliable tracking, below trigger threshold
  - after all selections (including following slides), only include events with a single D* candidate



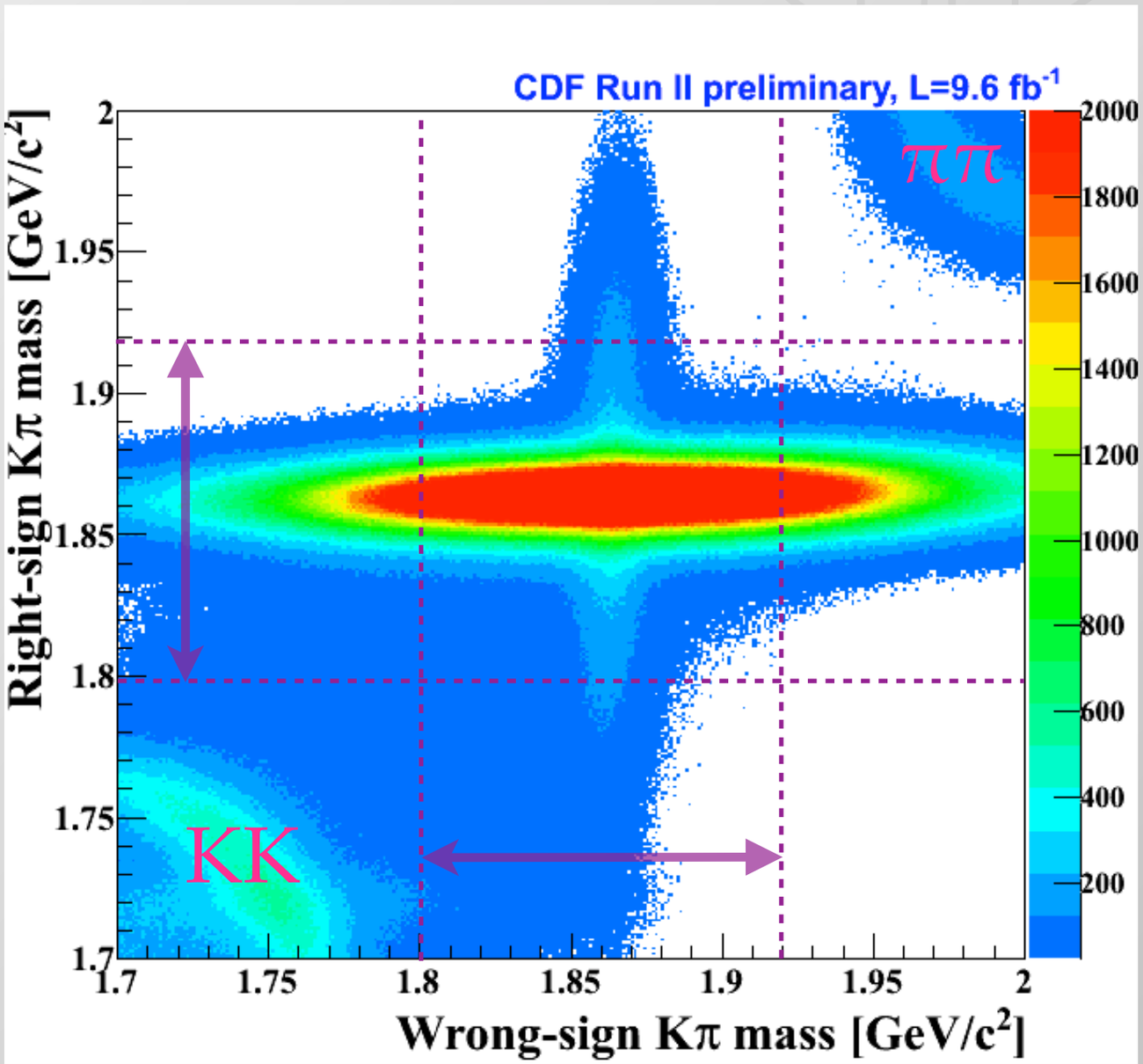
>8 x 10^6 time integrated RS D^0 (after all selections)

RS and WS Data

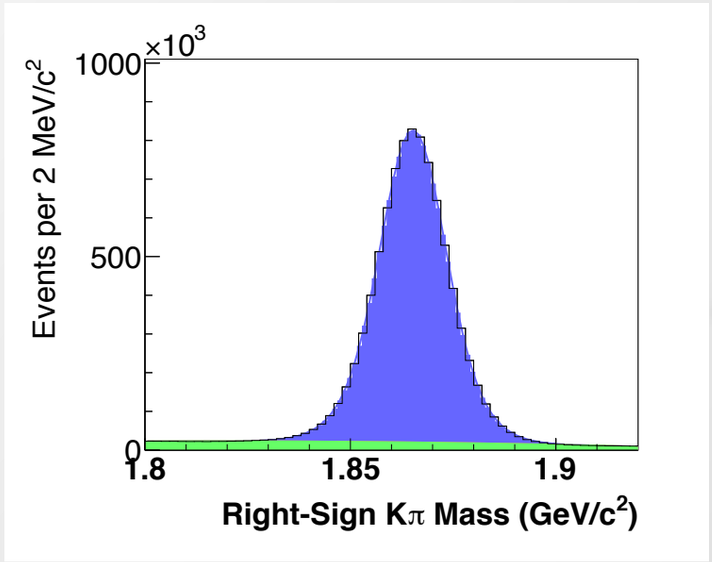
- D^0 candidates start with both $K\pi$ and πK particle assignments possible
- limit mass range to

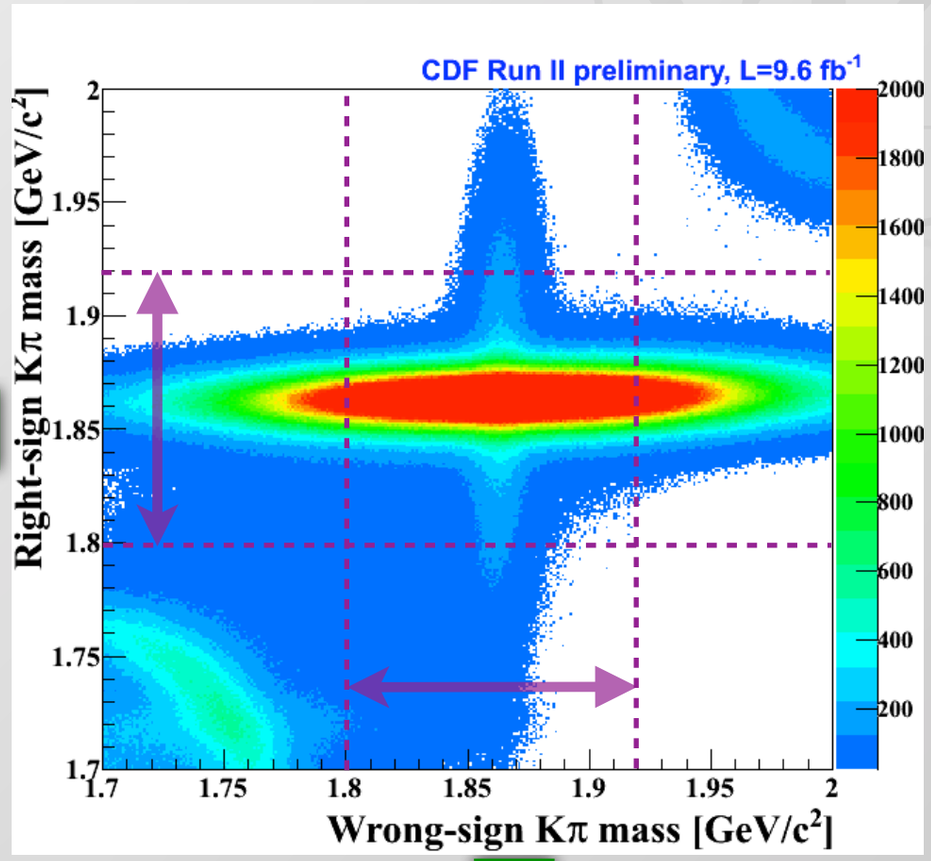
  $1.8 < m_{K\pi} < 1.92\ GeV/c^2$

  - Excludes $D^0 \rightarrow KK, \pi\pi$



RS and WS Data

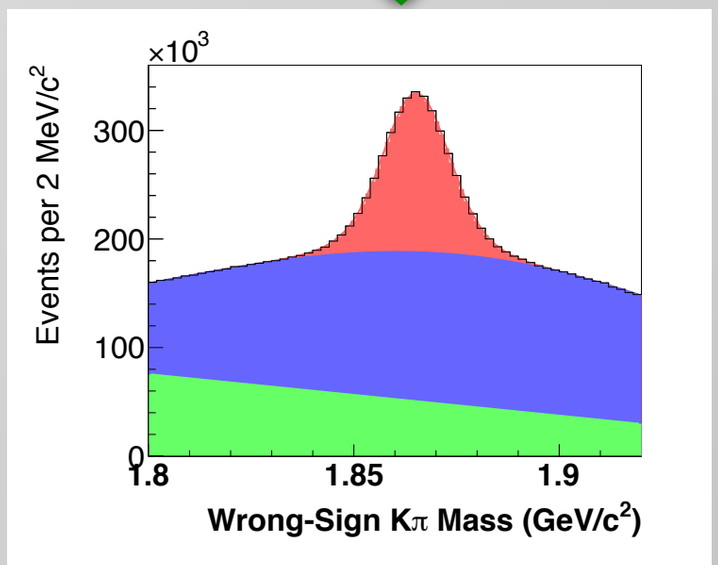




Blue events are consistent with correct D^0 reconstruction with the RS Kπ mass

Red events are consistent with correct D^0 reconstruction with WS Kπ mass

Green: other backgrounds

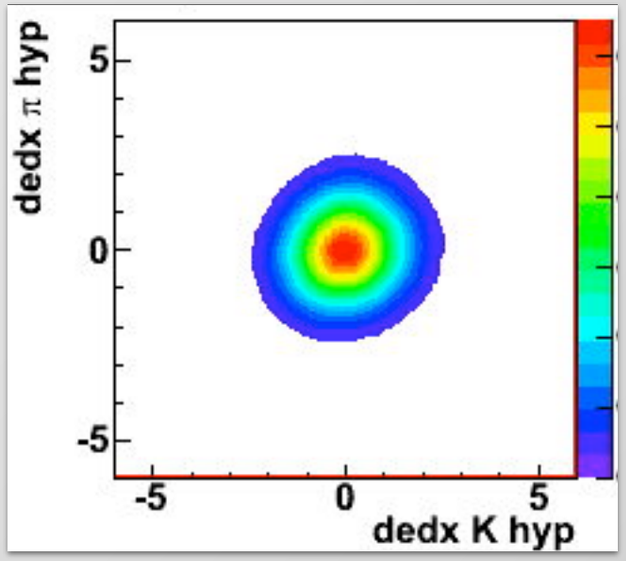


- Problem: Huge number of CF D^* (RS) events can mask WS signal
  - Swapping the Kπ particle assignments causes the distribution to get x10 wider than the correct assignments

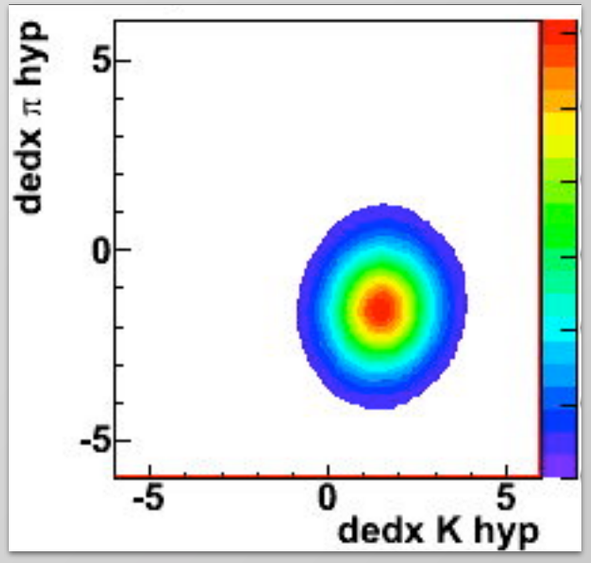
dE/dX Selection

- Correct particle assignment for a track results in the dE/dX part. id. variable having a Gaussian distribution with mean=0, width ~1
  - COT pulse height minus prediction for that type of particle, divided by error
- Incorrect assignment shifts the distribution away from zero
- Use both track part. id. at same time
  - Get "displacement" from zero,
  - Compare Kπ and πK track hypotheses, and keep the one closer to zero.

correct particle assignment

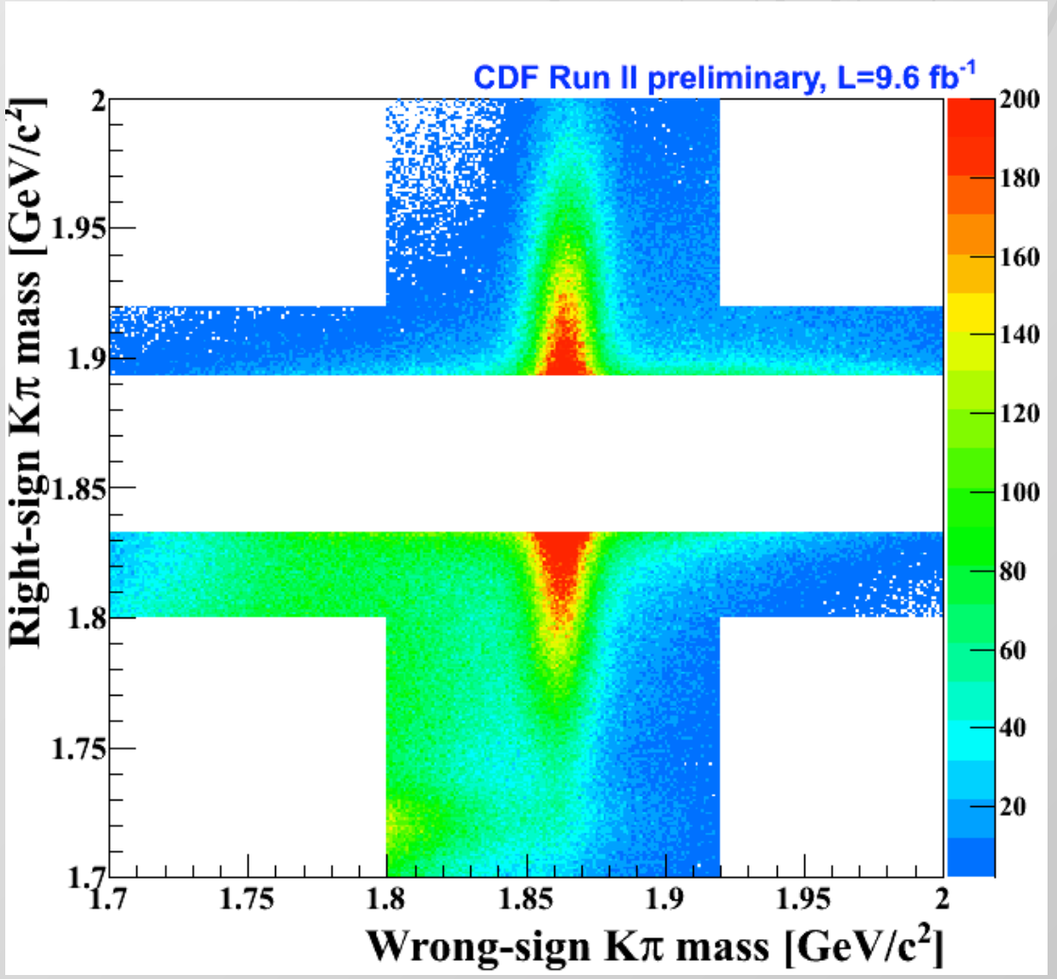


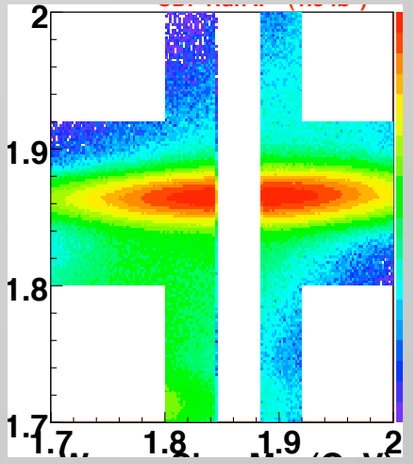
particles swapped



WS, RS Selection

- When projecting the WS mass, exclude candidates consistent with being a RS D^0
  - RS mass $|m_{K\pi} - m_{D0}| < 20$ MeV
  - Reduces signal by 1/3rd, but only a few % of background survives
- Exclude candidates consistent with WS D^0 when projecting the RS mass

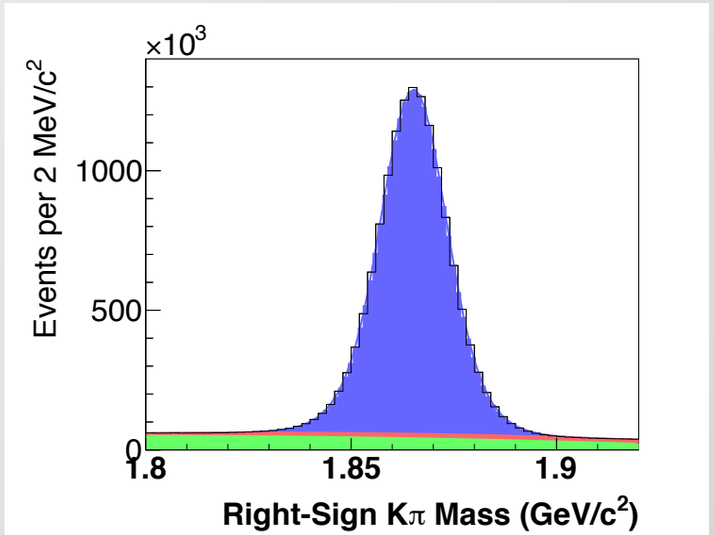


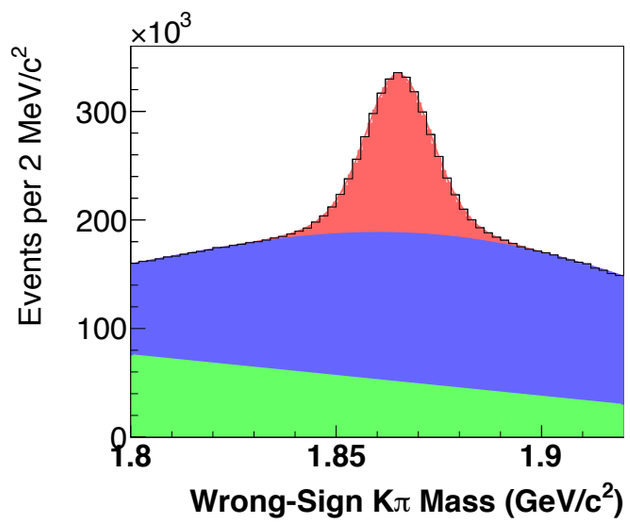


Mis-Assigned Clean-up

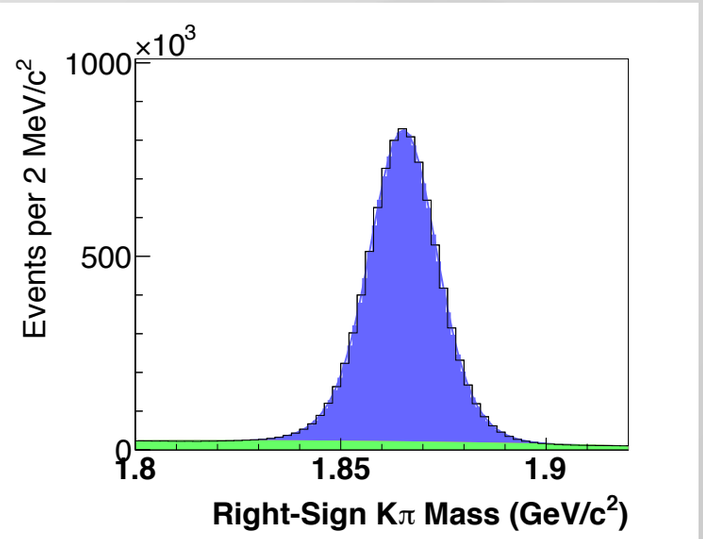
- Mass and PID cuts greatly clean up the CF D* background in the WS mass plots
- Sig/back improved ~120
  - Blue events are consistent with CF (RS) D* decays
  - Red events are WS D*, and background from fake D* (D0 + random track)
    - Green events are background

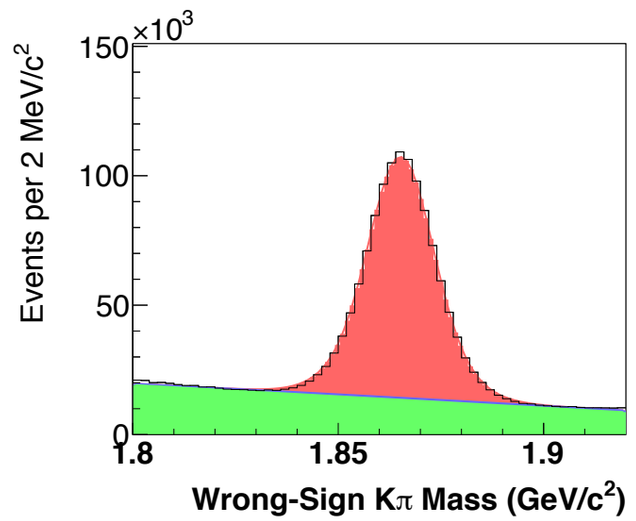
Before selections





After selections





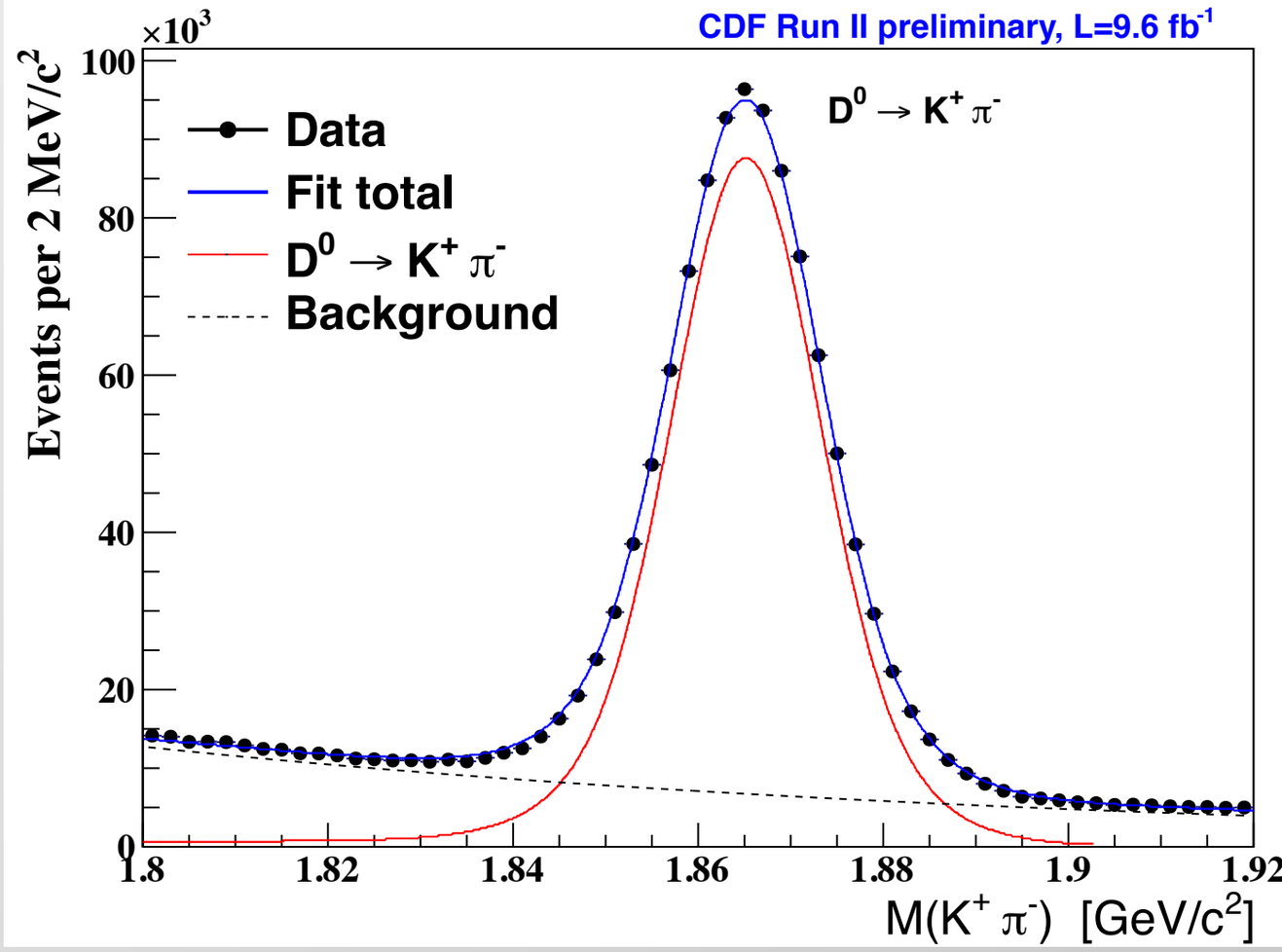
Fitting Methods

Analysis Overview

- Backgrounds to be accounted for
  - D* from B decays (not produced at beamline)
    - Make a correction in ratio R(t) to correct for the incorrect decay time
  - fake D* candidates
    - Fit ΔM plots to distinguish from real D*
  - fake D^0 -> $K\pi$ candidates
    - Fit $K\pi$ mass plots to distinguish from real D^0
- Start at the bottom and work towards the top
  - Each successive step has fewer backgrounds to worry about

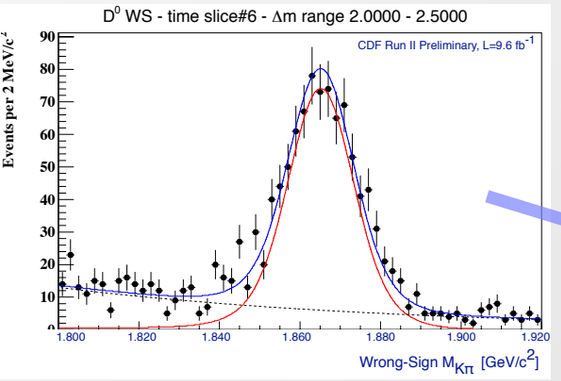
Kπ Mass Fits

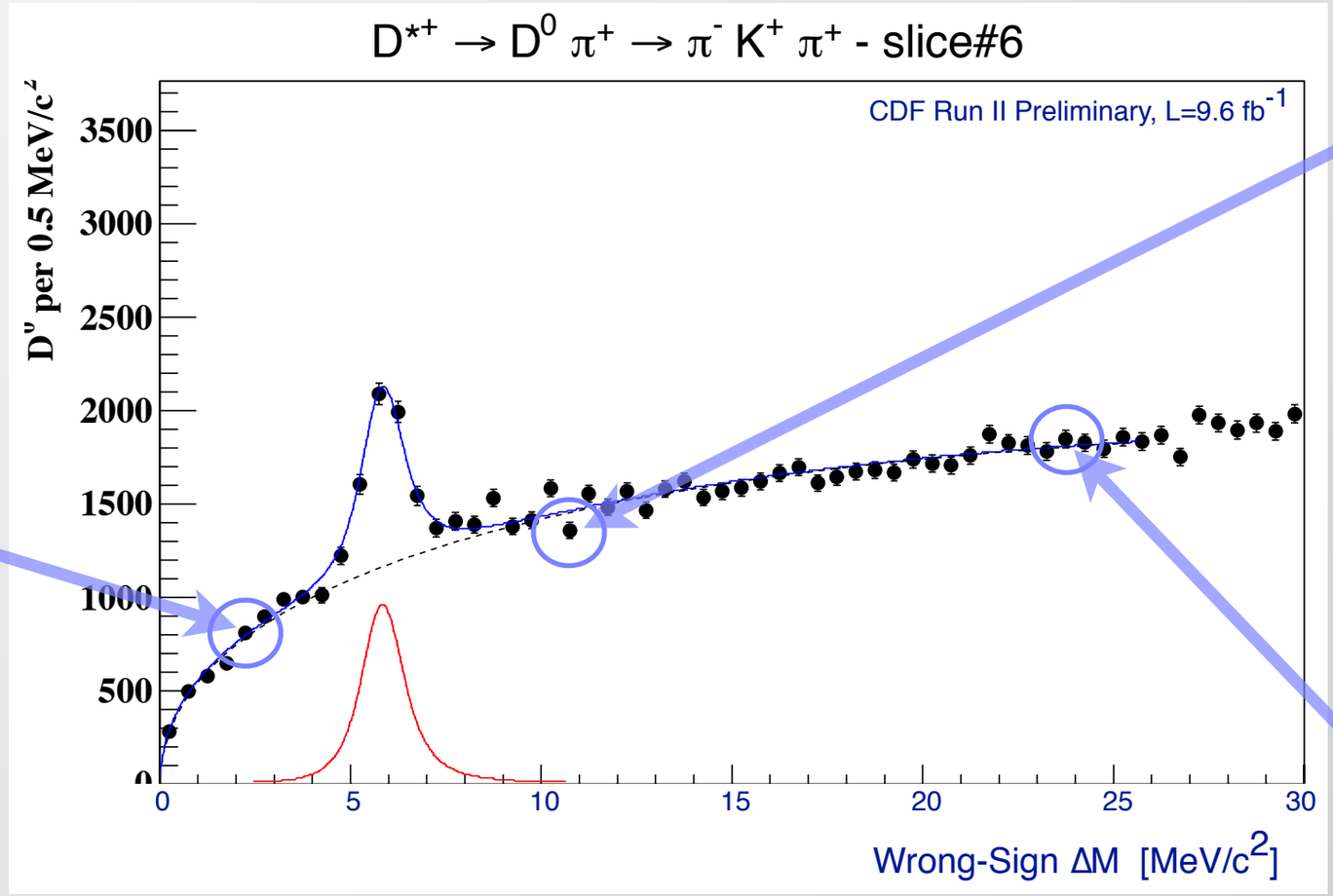
- Only correctly reconstructed D^0 -> Kπ forms a peak in the Kπ mass distribution
  - Backgrounds can be fit with an almost flat curve
- 2400 mass fits
  - data divided into: RS, WS; 20 time bins; 60 bins of ΔM
- Same D^0 signal shape used for RS and WS
- Parameters for background are independent for all fits

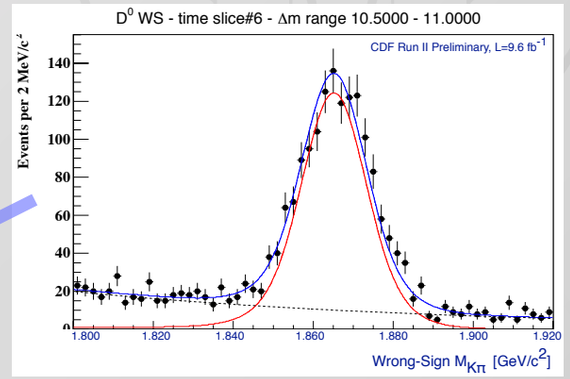


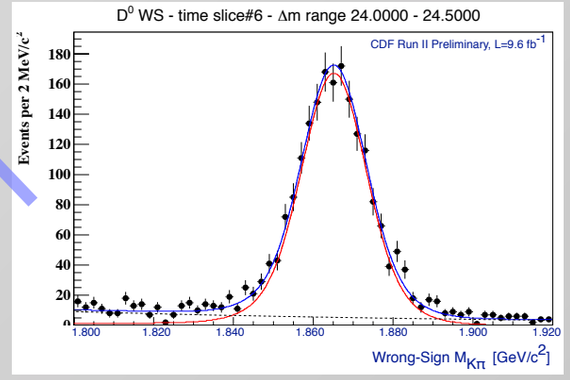
WS Kπ mass, time and ΔM integrated
(for illustration purposes)

Mass Diff. Yields





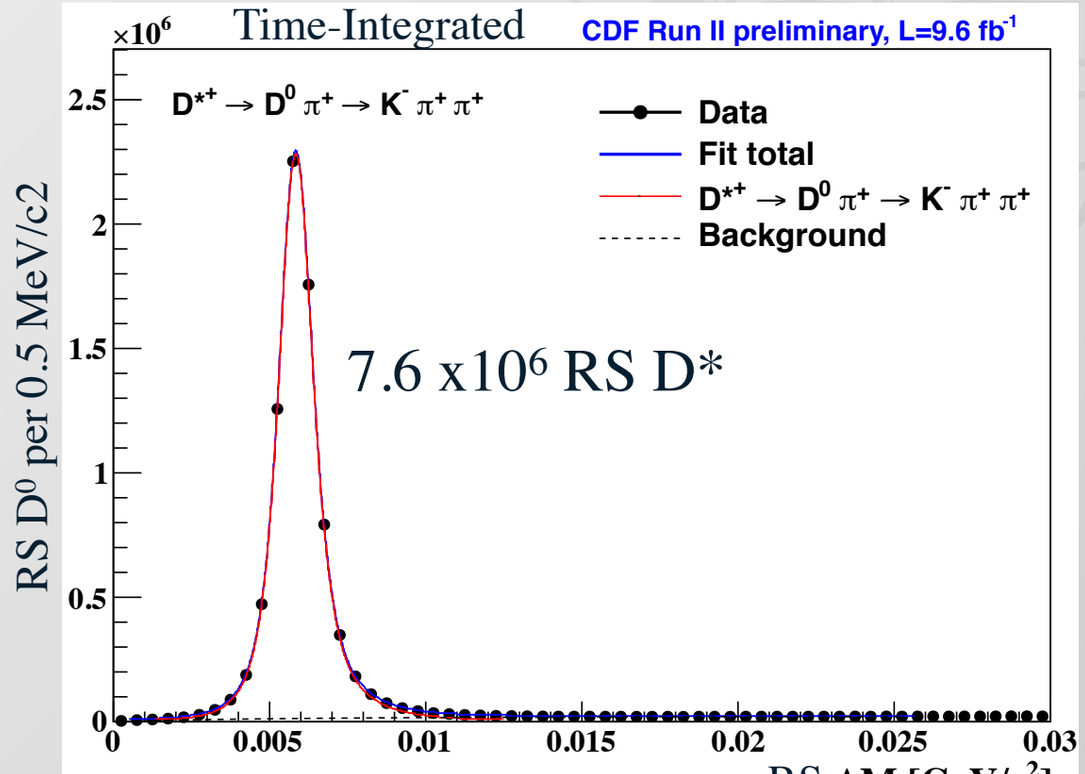


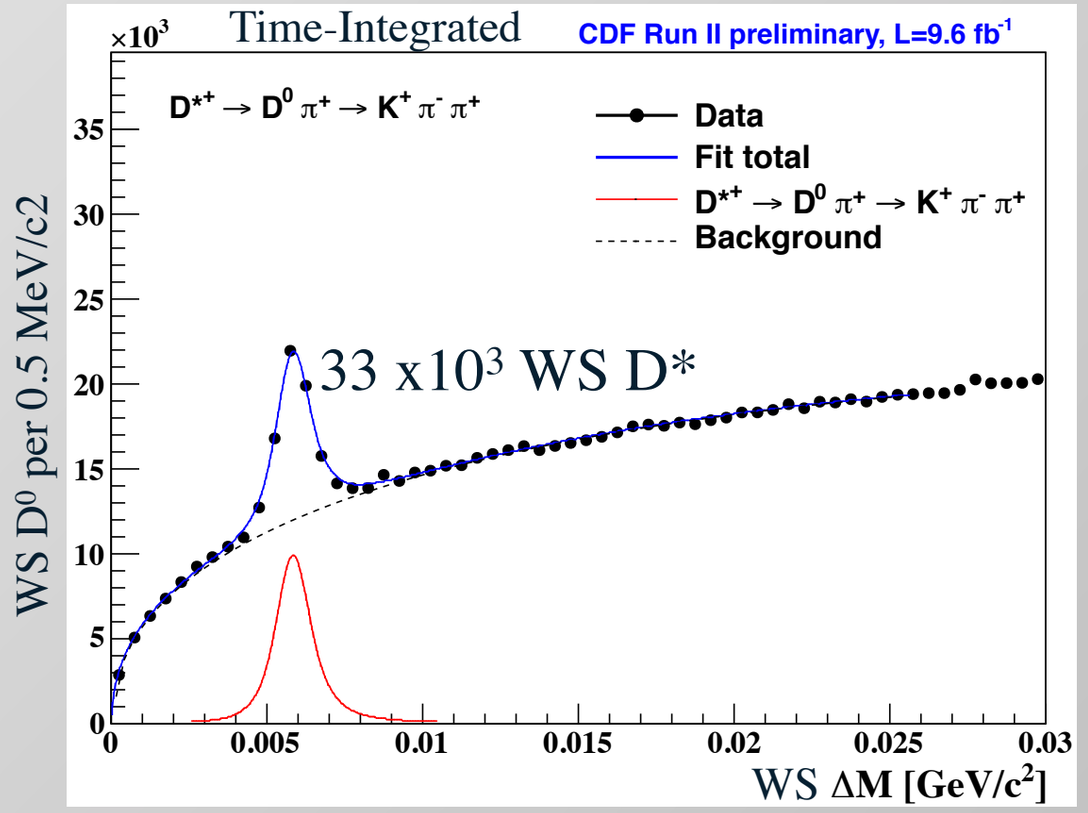


- Use results of the Kπ fits to get D^0 versus ΔM distribution
  - each point --> number of D^0 from a Kπ fit
  - error bars are the uncertainty on # of D^0 from Kπ fit

ΔM fits

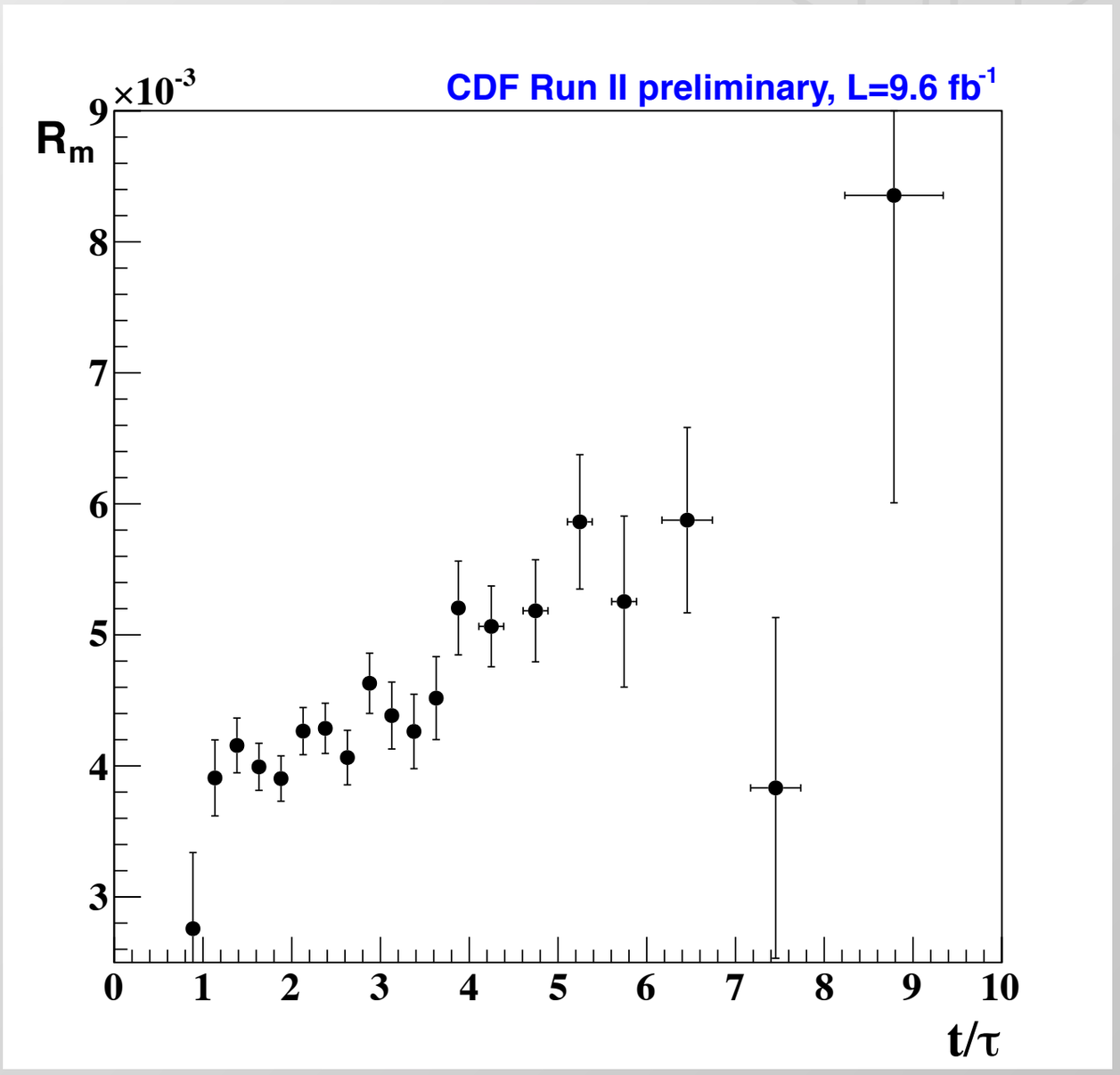
- 40 fits for D* yield
  - RS, WS; 20 time bins
- RS and WS D* have the same signal shapes
- Independent parameters for signal and background amplitudes for all time bins
  - Only events in these plots are D* and (D^0 + random track)





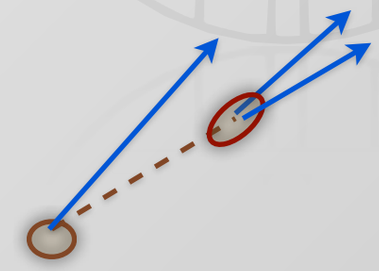
WS/RS Ratio

- Use the 20 RS D* yield and 20 WS D* yield plots to get the WS/RS ratio in our time bins
- Some of these D* were produced at the beamline
- Some of these D* were not produced at the beamline
  - Decay time measured from the beamline will be incorrect
  - Want to correct for the effect of these events on the WS/RS ratio

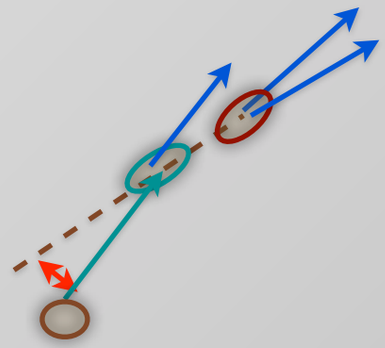


Secondary D*

- D* produced from B-decays will have the wrong proper decay time
  - decay length is measured from the primary vertex to the D^0 vertex
  - Since the B lifetime to D lifetime is ~4:1, most of these background D* will be short decay-time D^0 shifted to longer analysis time bins
- Extrapolate the D^0 towards the primary vertex
  - d_0 : impact parameter
  - D* produced at a secondary vertex will have a larger d_0 value



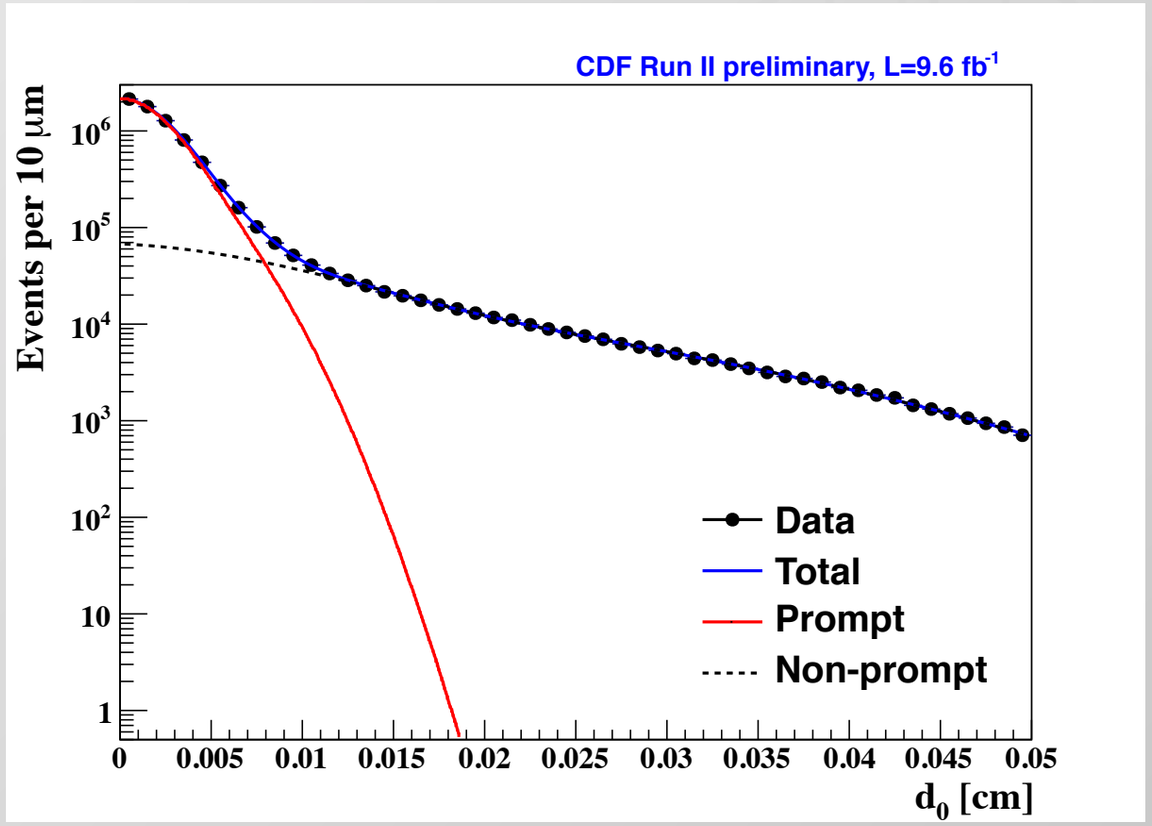
D* produced at the beamline
33 μm beam spot size



D* from B decay
Decay length from beamline
is longer than the D^0 decay length

Impact Parameter

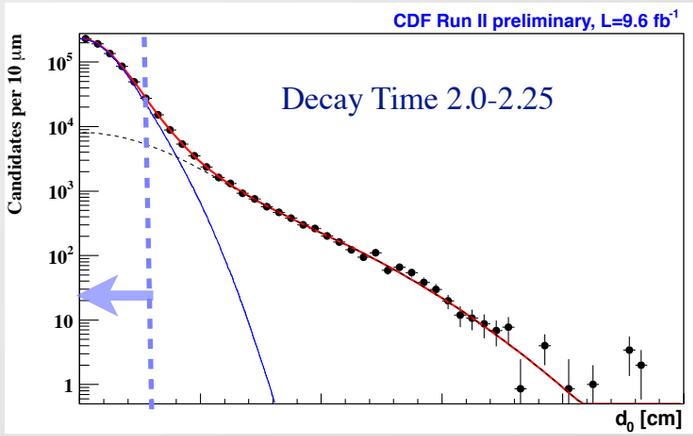
- D* produced at the primary vertex have a narrow, time-independent impact parameter (d_0) distribution
  - confirmed with data and MC
- D* from B decays have a wider, time-dependent distribution
  - width increases with decay time
  - fit distribution using RS signal

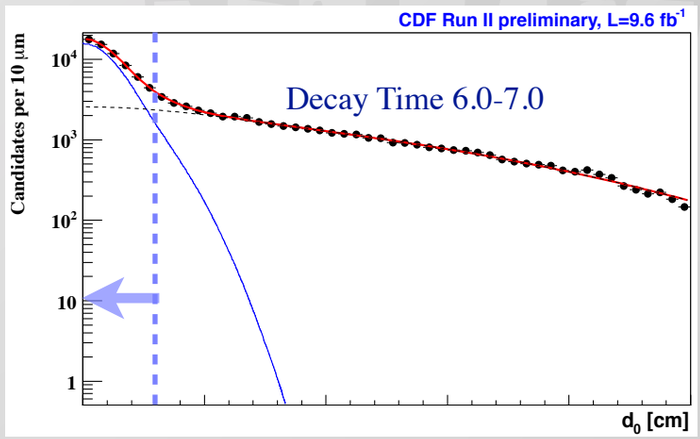


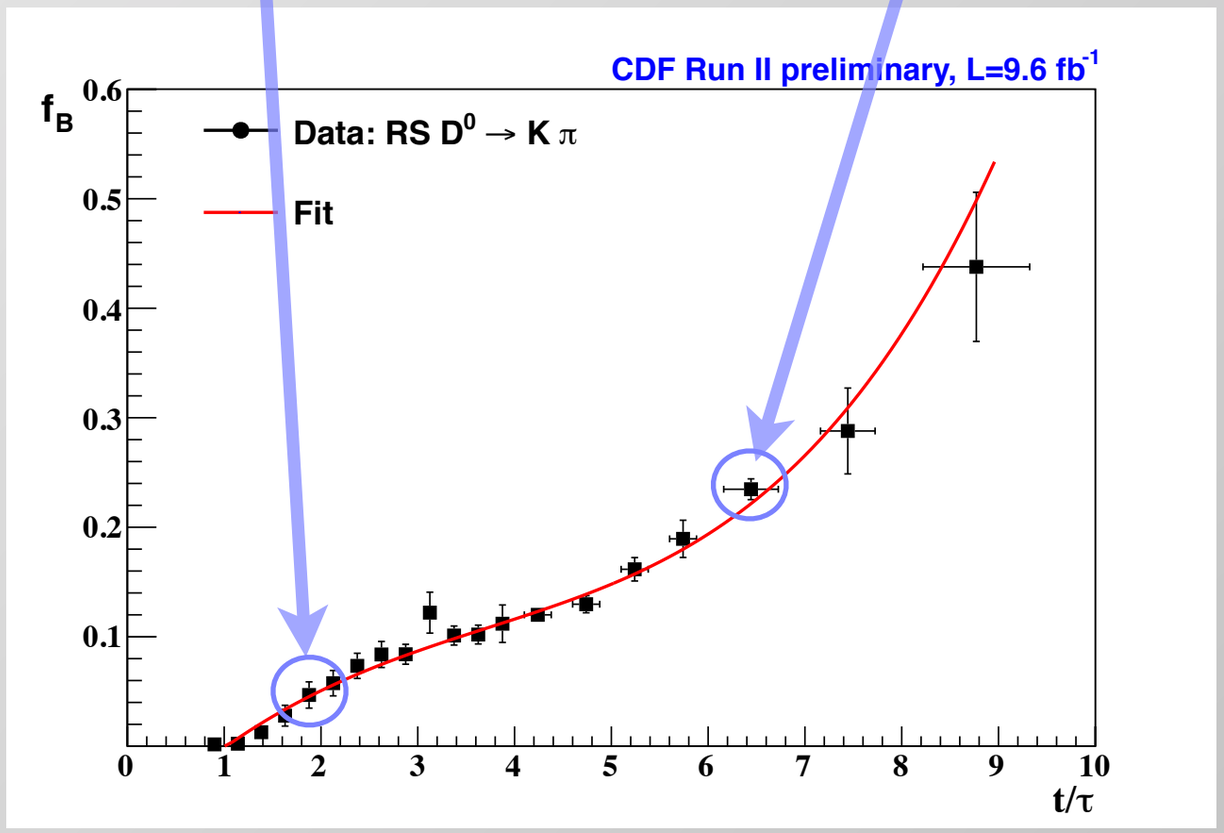
Time-integrated RS distribution

Impact Parameter

- For each analysis time bin, fit the prompt and non-prompt distributions
  - prompt-shape: double Gaussian
  - non-prompt: double Gaussian, each time bin is independent of the others
- Use these fits to determine $f_B(t_i)$, the fraction of RS D* (with d_0 < 60 μm) that come from B-decays
  - Fit with 4th-order polynomial (empirical)







Secondary WS/RS Ratio

$$R_B\left(t_i\right) = \frac{\sum_{j=1}^{M} \tilde{h}_{ij} R(t'_j)}{\sum_{j=1}^{M} \tilde{h}_{ij}}$$

- Use MC simulation to get the WS/RS ratio R_B
  - For each analysis time bin (t_i), get the distribution h_{ij} of D^0 decay times, if we knew the B to the D^0 decay time (t'_j)
  - Use the predicted ratio formula R(t), but with the "correct" time (t'_j) for this type of background

$$R(t/\tau) = R_D + (t/\tau)\sqrt{R_D}\, y' + (t/\tau)^2 \frac{x'^2 + y'^2}{4}$$

WS/RS Fit χ^2 Function

Instead of comparing the data points directly to the predicted ratio formula...

$$\chi^2 = \sum_{i=1}^{20} \frac{1}{\sigma_i^2} \left(R(t_i) - r_i \right)^2$$

$$R(t) = R_D + (\Gamma t)\sqrt{R_D}\, y' + (\Gamma t)^2 \frac{x'^2 + y'^2}{4}$$

... use the formula that includes D* background from secondary decays.

ratio prediction: includes contribution from "beamline" and "B decay" D*

term for uncertainty on the MC time distribution

$$\chi^2 = \sum_{i=1}^{20} \frac{1}{\sigma_i^2} \left(\left(1 - f_B(t_i) \right) R(t_i) + f_B(t_i)\, R_B(t_i) - r_i \right)^2 + C(f_B) + C(h_{ij})$$

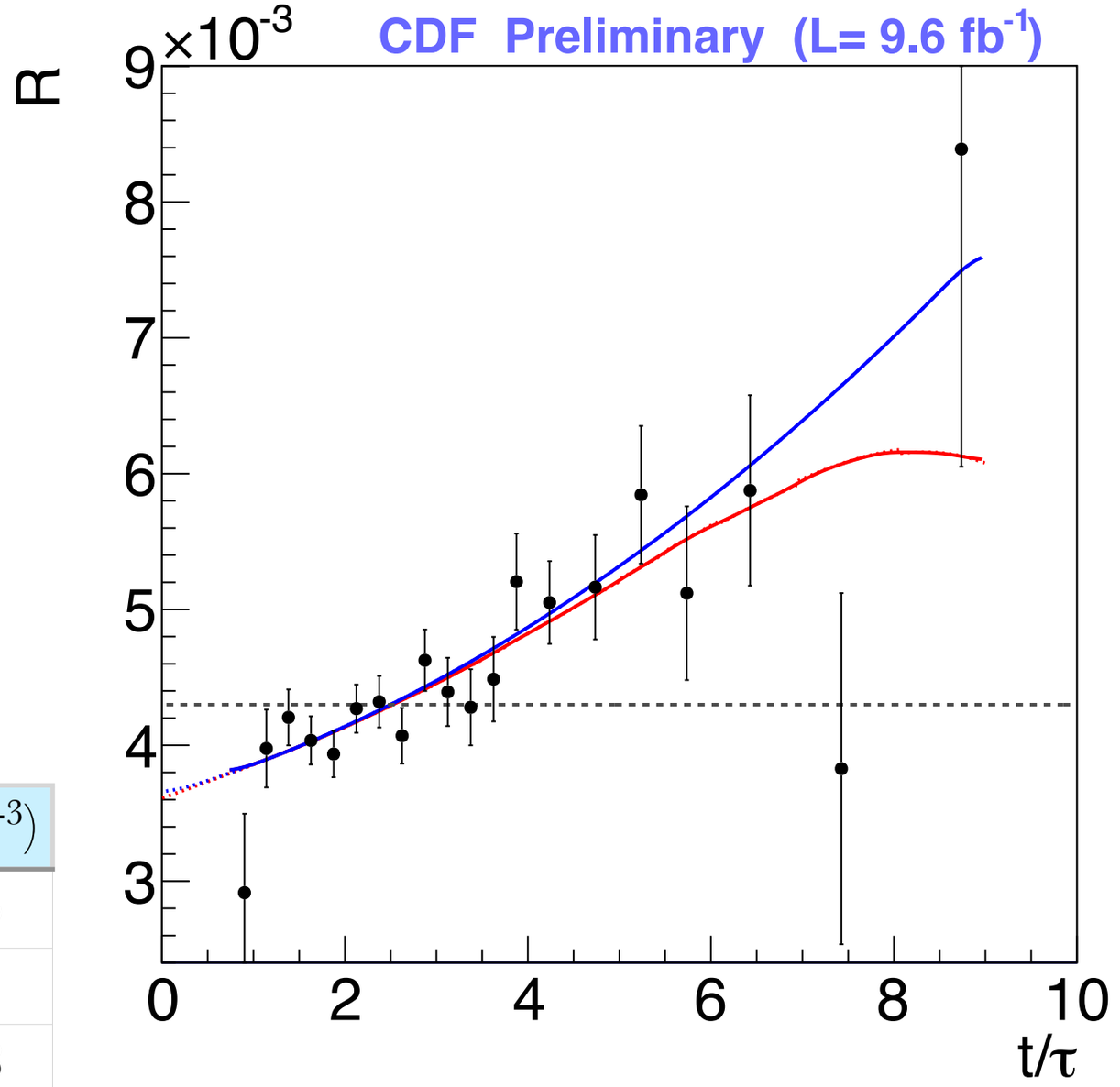
term for the uncertainty on the secondary fractions f_B

Systematic Studies

- The uncertainties stated includes the errors returned by the mass fits and uncertainties on the fractions f_B and the simulation time distributions.
- Investigated possible effects that could bias the result
  - Variation of D^0 signal shape
  - D* signal shape
  - partially reconstructed charm background in $K\pi$ fits
  - D* background shape
  - impact parameter non-prompt shape
  - simulation time scale
  - detector track reconstruction asymmetries
- The systematic uncertainties were found to be small relative to the statistical errors from data
  - For many of these, there is a common effect on the WS D* and RS D* fits, and the effect cancels in the WS/RS ratio

Ratio Result

- Dashed line is the fit assuming no-mixing (no time dependence)
- Red line is the fit including the contribution D* from secondary decays
- Blue is the projection of the parameters, if there were no D* from B-decays



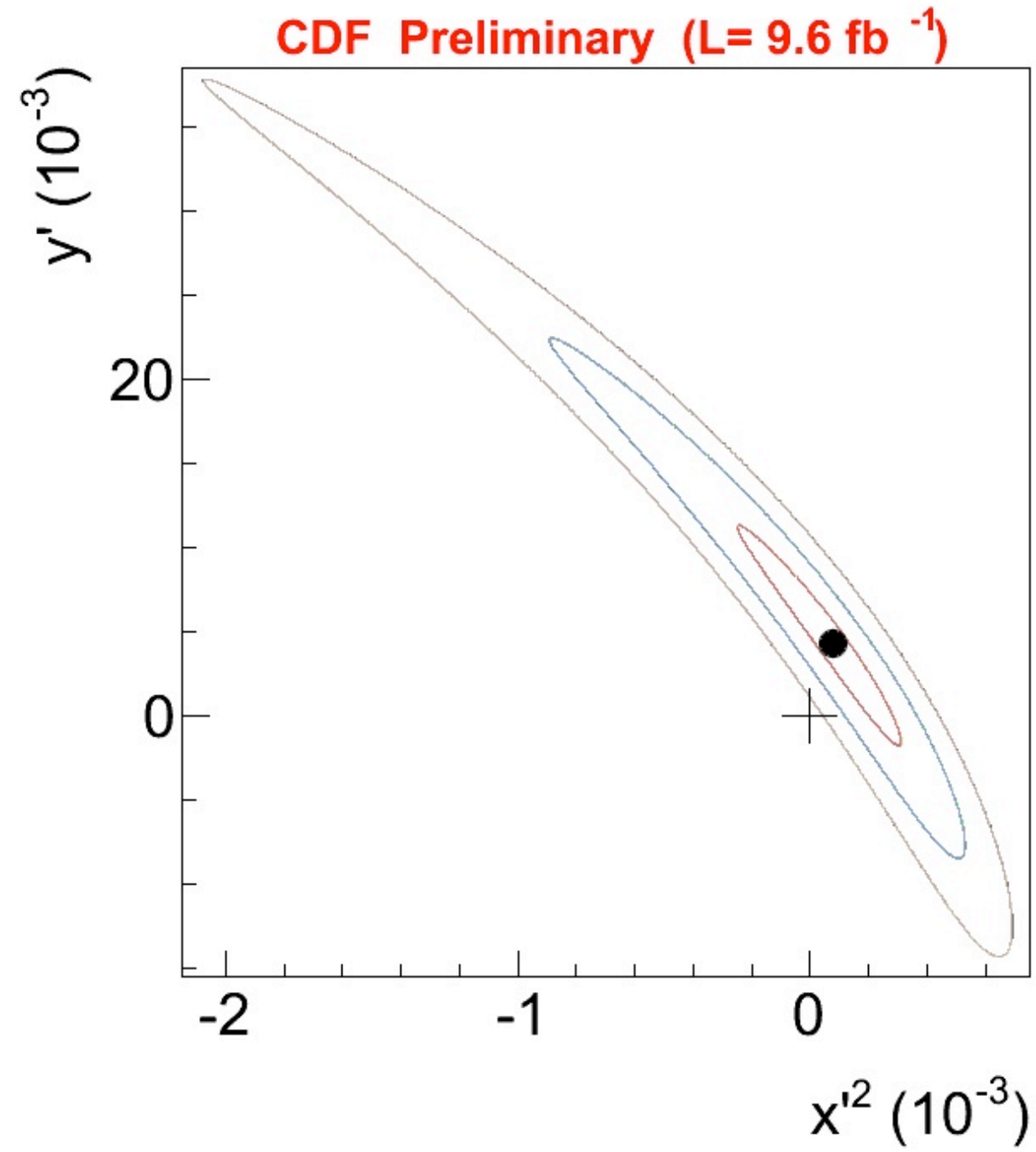
Fit Type	χ^2 /ndof	Parameter	Fit Value (10^{-3})
		R_D	3.51 ± 0.35
Mixing	16.91/17	y'	4.3 ± 4.3
		x'^2	0.08 ± 0.18
No-mixing	58.75/19	R_B	4.30 ± 0.06

Correlation Coefficients		
R_D	y'	x'^2
1	-0.967	0.900
	1	-0.975
		1

Probability Contours

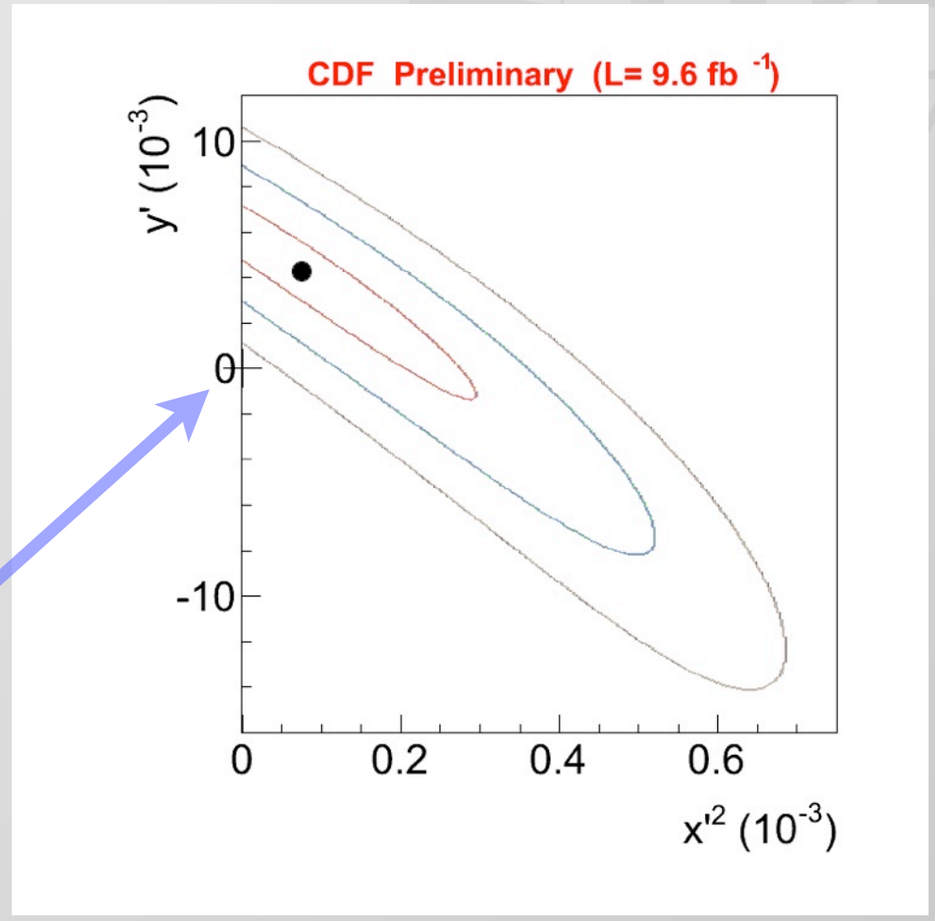
- Bayesian probability intervals equivalent

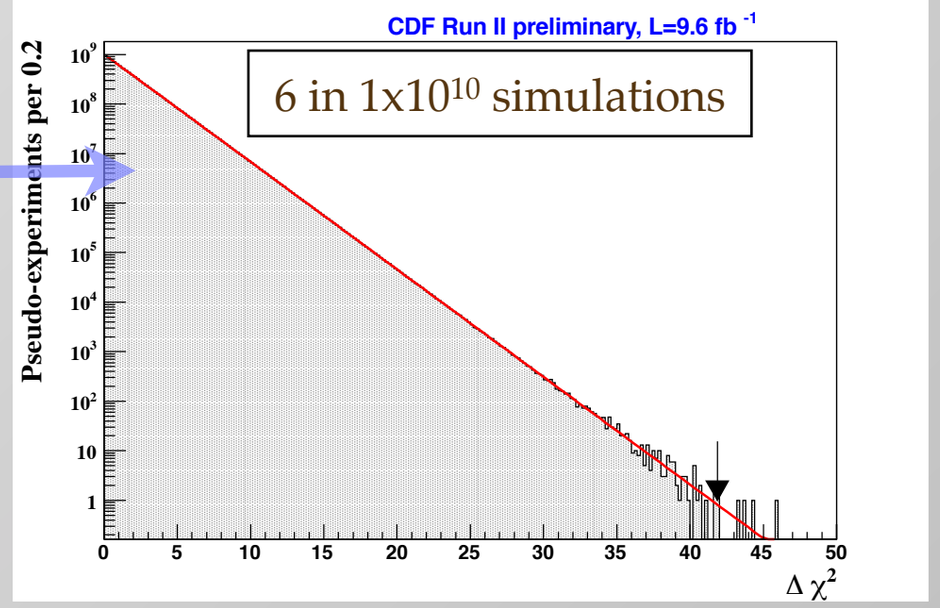
  to 1, 3, and 5 σ
  - likelihood ~ exp(-χ^2 /2)
    - solid point = best fit
    - cross = no-mixing ($y'=x'^2=0$)
      - x' is a real number, so fits with $x'^2<0$ are unphysical
- Bayesian probability contour that excludes no-mixing point is equivalent to 6.1σ



No-mixing Significance

- Alternative checks of the significance
- All resulted in exclusion at 6.1σ significance
- Bayesian probability restricted to $x'^2 \geq 0$
- Probability for $-2\Delta\log(L) = 41.8$, between best fit and no-mixing point, assuming χ^2 distribution with 2 d.o.f.
- p-value (frequentist): Number of toy simulations with $\Delta\chi^2 \geq 41.8$





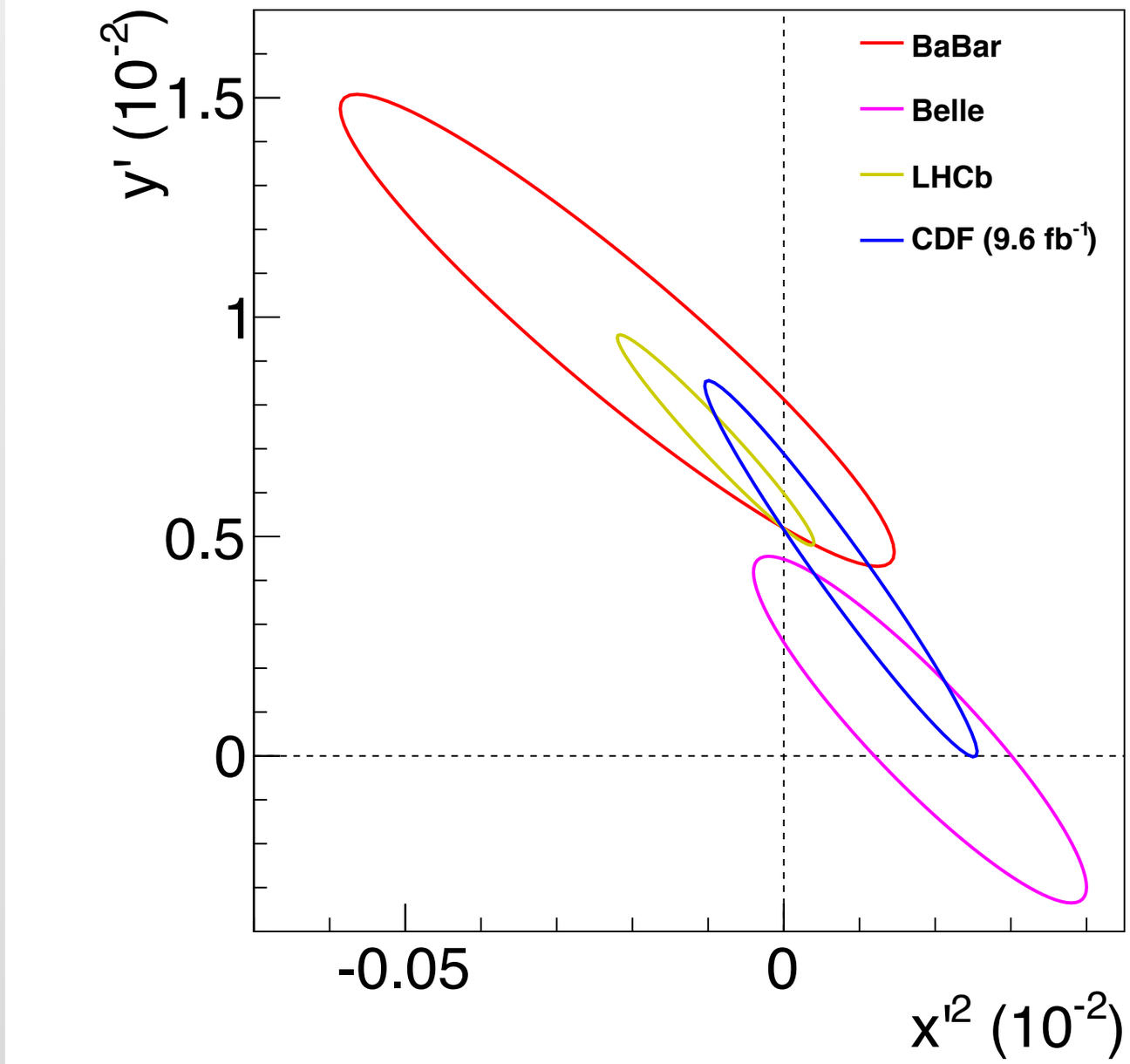
Experiment Results

Experiment	R_D ($x10^{-3}$)	y' ($x10^{-3}$)	x'^2 ($x10^{-3}$)	Excl. No-Mix Significance	R_B ($x10^{-3}$)
Belle (2006)	3.64 ± 0.17	0.6 ± 4.0	0.18 ± 0.22	2.0	3.77 ± 0.09
BaBar (2007)	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9	3.53 ± 0.09
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13	9.1	4.25 ± 0.04
CDF (9.6/fb)	3.51 ± 0.35	4.27 ± 4.30	0.08 ± 0.18	6.1	4.30 ± 0.06

- In this table, "R_B" (PDG notation) means the fit assuming no-mixing (or the time-integrated ratio).
- "R_D" is the parameter for the mixing fit, for the ratio at t=0

Mixing Comparisons

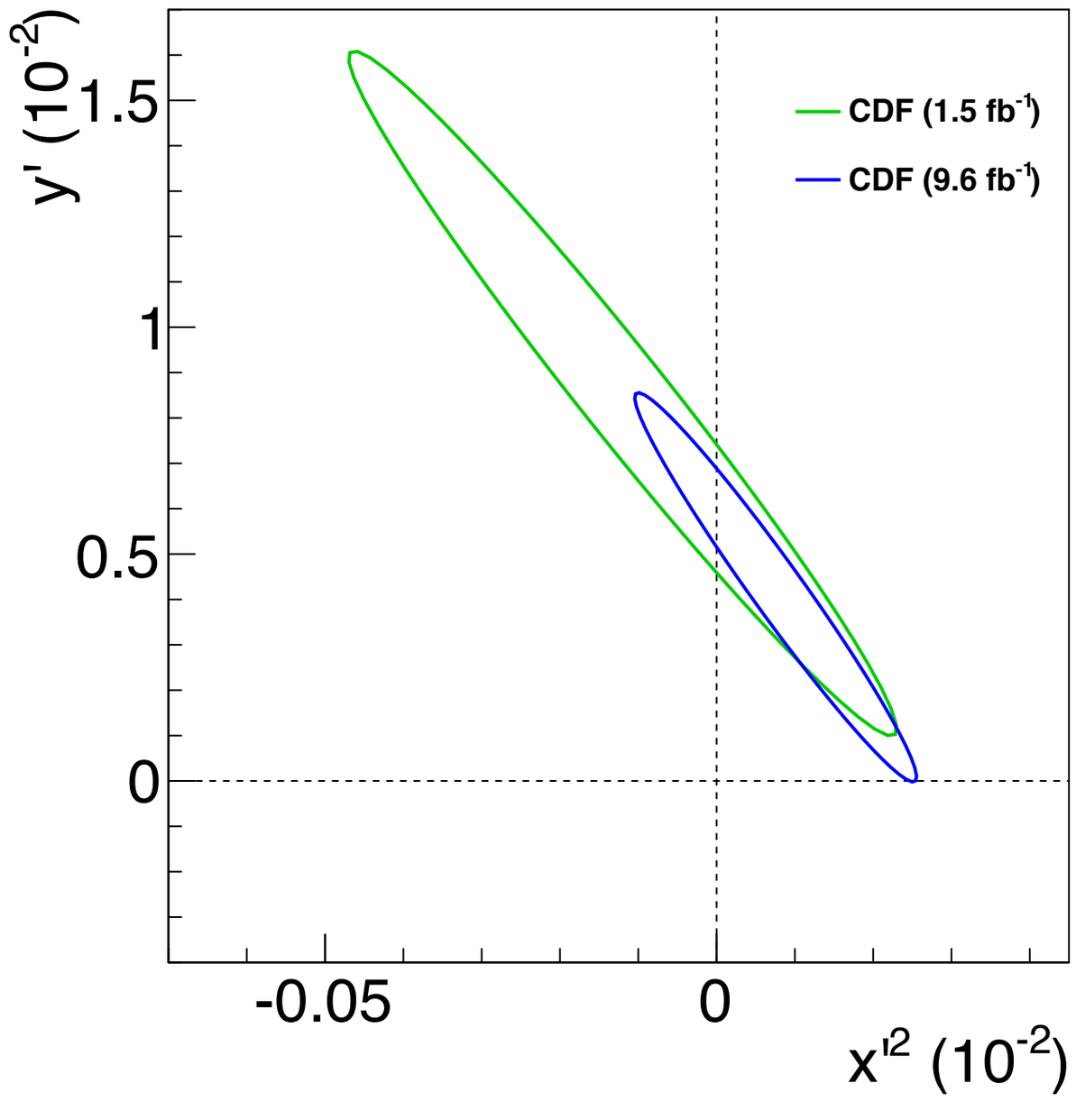
- Difficult to get full contours from all experiments
- As an approximation, make 1σ contours based on the fit parameters errors and y'-x'^2 correlations



Conclusion

- We measured charm mixing in the D^0->Kπ channel using the full CDF data set
- We confirm LHCb observation of charm mixing (from a single decay channel measurement)
- CDF measurement contributes important statistical precision to mixing parameters
- New physics may emerge from future precision measurements combined with advances in theory

Backup - Prev Result

Experiment	R_D ($x10^{-3}$)	y' ($x10^{-3}$)	x'^2 ($x10^{-3}$)	Excl. No-Mix Significance	R_B ($x10^{-3}$)
Belle (2006)	3.64 ± 0.17	0.6 ± 4.0	0.18 ± 0.22	2.0	3.77 ± 0.09
BaBar (2007)	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9	3.53 ± 0.09
CDF (1.5/fb)	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8	4.15 ± 0.10
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13	9.1	4.25 ± 0.04
CDF (9.6/fb)	3.51 ± 0.35	4.27 ± 4.30	0.08 ± 0.18	6.1	4.30 ± 0.06

Backup - Prev Result